Finnish Energy – Low carbon roadmap

FINAL REPORT

1 JUNE 2020

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List of abbreviations

BAU	Business as usual (scenario)
CCGT	Combined cycle gas turbine
CCS	Carbon storage and storage
CHP	Combined heat and power
COP	Coefficient of performance
CSP	Concentrated solar power
DH	District heating
EV	Electric vehicle
FLH	Full-load hours
GW	Gigawatt
HOB	Heat-only boiler
HVA C	Heating, ventilation and air conditioning
kW	Kilowatt
LCOE	Levelised cost of energy
LCOH	Levelised cost of heat
MW	Megawatt
MWh	Megawatt hour
P2G	Power to gas
PV	Photovoltaic
RES	Renewable energy sources
SMR	Small modular (nuclear) reactor
TWh	Terawatt hour

Tiivistelmä

Päästötöntä sähköntuotantoa tarvitaan merkittävästi lisää teollisuuden vähähiilitiekarttojen seurauksena

- Energiaintensiivisen teollisuuden vähähiilitiekarttojen skenaariot johtavat sähkön kysynnän merkittävään kasvuun Suomessa nykykehitykseen verrattuna
  - Erityisesti investoineilla prosessilämmön ja vedyn tuotannon sähköistymiseen on raju vaikutus Suomen sähkön kysyntään vuoteen 2035 mennessä ja vielä enemmän vuonna 2050
  - Lisääntynyt teollisuuden sähkön kysyntä vähähiiliskenaariossa lisää samalla merkittävästi kysyntäjoustopotentiaalia
  - Kaikkia kysyntäjouston lähteitä tulisi kehittää aktiivisesti järjestelmän tasapainottamiseksi uusiutuvan sähköntuotannon lisääntyessä olennaisesti
- Uuteen sähköntuotantokapasiteettiin vaaditaan merkittäviä investointeja voimakkaasti lisääntyvän sähkön kysynnän seurauksena
  - Investointeja uuteen kapasiteettiin tarvitaan selvästi nopeammin verrattuna perusskenaarioon
  - Päästöttömän sähköntuotannon kustannukset ovat laskeneet rajusti viimeisen vuosikymmenen aikana ja kustannusten oletetaan laskevan edelleen
  - Sähkön hintanäkymän tulisi antaa markkinoille riittävän luotettava signaali, jotta investoinnit tapahtuvat riittävällä tahdilla
- Investointeja tarvitaan myös siirtoverkkoon, jotta päästötön sähköntuotanto saadaan siirrettyä tuotantopaikalta kulutuksen luo ja voidaan hyödyntää laajemman markkina-alueen tuoma jousto kysynnän ja tarjonnan tasapainottamiseksi
  - Säästä riippuvan tuulivoimatuotannon ja sähkön kysynnän voimakas lisääntyminen vaatii erittäin vahvoja rajasiirtoyhteyksiä ja tehokkaasti toimivat sähkömarkkinat maiden välillä, jotta järjestelmä pysyy tasapainossa eri sääolosuhteissa eri aikoina
  - Sähkön kysynnän lisääntyminen keskittyy teollisuuskohteiden lisäksi asutuskeskuksiin liikenteen ja lämmityksen sähköistymisen myötä
  - Siirtoverkkoinvestointien toteutusajat ovat pitkiä ja erilaiset joustomahdollisuudet tulisi huomioida mahdollisissa pullonkaulatilanteissa

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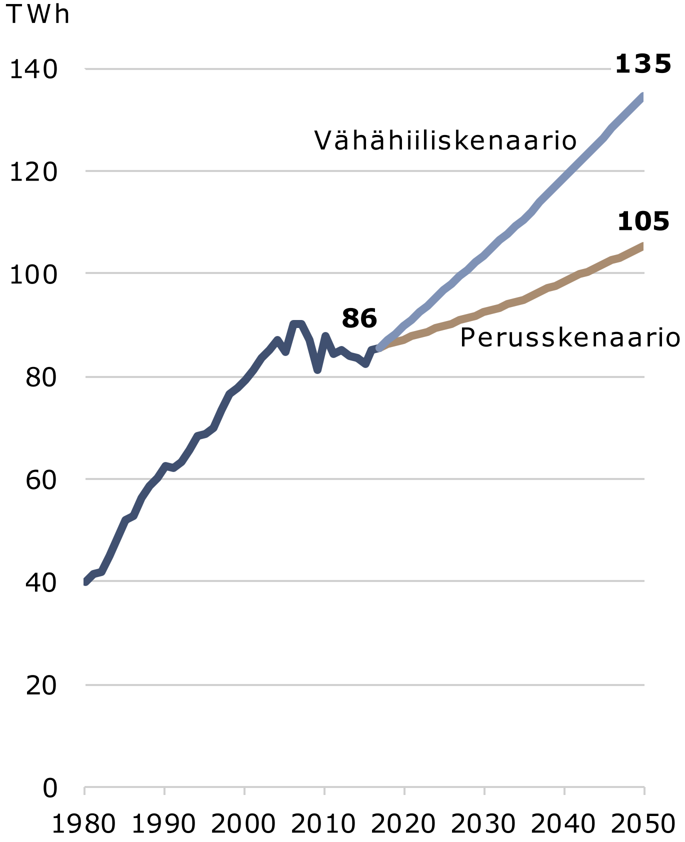
Kaukolämmöllä ja yhteistuotannolla on merkittävä rooli hiilineutraalissa yhteiskunnassa

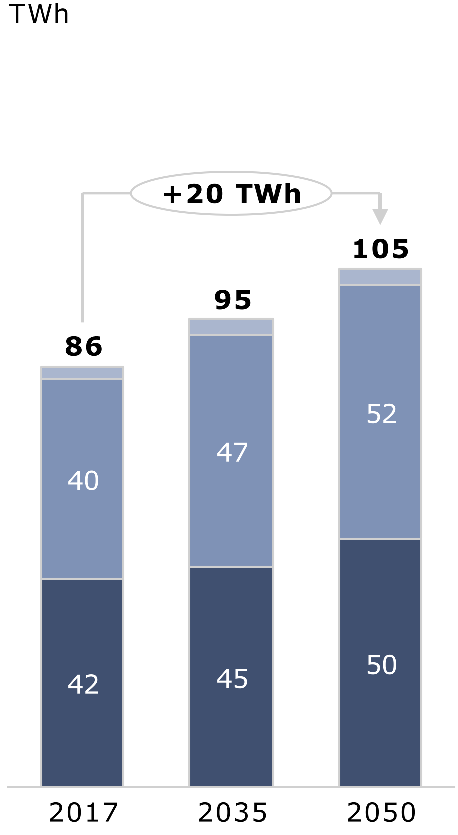
- Sähkön kysynnän merkittävä kasvu lisää yhteistuotannon roolia vähähiiliskenaariossa sähköjärjestelmän toimitusvarmuuden varmistamiseksi
  - Tällä on suora vaikutus biomassan kysyntään, jonka osuus polttoaine-mixissä kasvaa voimakkaasti perus- ja vähähiili-skenaarioissa
  - Lämpöpumppujen ja geotermisen lämmön nähdään kasvattavan osuuttaan kaukolämmön tuotannossa
  - Geotermisen lämmön teknis-taloudelliseen potentiaaliin liittyy edelleen epävarmuuksia , mutta skenaarioissa sen on oletettu olevan kypsä markkinoille vuoteen 2035 mennessä
  - Uudet teknologiat, kuten modulaariset ydinreaktorit (SMR) ja keskittävät aurinkokeräimet (CSP), ovat myös potentiaalisia vaihtoehtoja tulevaisuudessa
- Kaukolämpöjärjestelmät tarjoavat joustoa energiajärjestelmään usealla tavalla
  - Yhteistuotanto tarjoaa joustoa usealla eri aikajänteellä, koska sähkön tuotannon profiili korreloi hyvin sähkön kulutuksen profiilin kanssa vuoden ja päivän sisällä
  - Lämpöpumput ja sähkökattilat voivat hyödyntää alhaisia sähkön hintoja ja voivat tarjota kysyntäjoustoa järjestelmän tasapainottamiseksi
  - Kaukolämpövarastot lisäävät joustopotentiaalia
  - Älykkäät ohjausratkaisut ja palvelualustat mahdollistavat asiakkaiden oman tuotannon ja kysyntäjouston potentiaalin hyödyntämisen
- Kaasun käyttö sähkön tuotannossa vähenee nykyisen kapasiteetin poistuessa markkinoilta, mutta tätä korvaa osittain lisääntynyt kaasun käyttö teollisuuden vähähiilitiekarttojen skenaarioissa

Vähähiilinen kehityspolku lisää teollisuuden sähkön kysyntää Suomessa merkittävästi verrattuna normaaliin kehitykseen

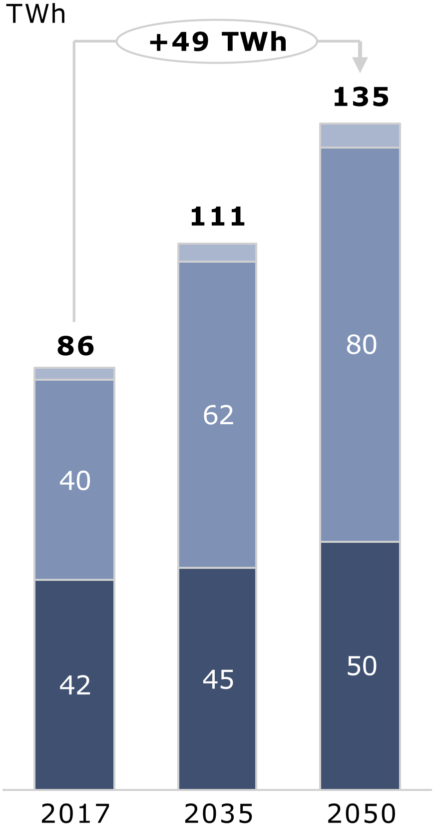
SÄHKÖN KYSYNNÄN MAHDOLLISET KEHITYSPOLUT SUOMESSA



PERUSSKENAARIO



VÄHÄHIILISKENAARIO



- Verkkohäviöt
- Teollisuus
- Muut sektorit

SKENAARIO-OLETUKSET

Sähkön kysynnän skenaariot perustuvat teollisuuden vähähiilitiekarttoihin ja tarkasteltuihin julkisiin kysynnän ennusteisiin

- **Teollisuuden** kysyntä perustuu pääosin meneillä oleviin sektorikohtaisiin vähähiilitiekarttoihin
- **Muiden sektoreiden** kysyntä perustuu AFRY:n tekemään katsaukseen viimeaikaisista tutkimuksista ja pysyy samana molemmissa skenaarioissa
- **Verkkohäviöiden** oletetaan olevan n. 3 % kulutuksesta

Lähde: AFRY:n analyysi

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Vähähiiliskenaarion korkeampaan sähkön kysyntään vastataan etenkin ydin- ja tuulivoimatuotannolla, joiden osuus tuotannosta kasvaa merkittävästi

KOMMENTIT VÄHÄHIILISKENAARIOSTA

CHP-tuotantokapasiteetti laskee hieman

- Nykyisistä CHP-laitoksista korvataan useampi vastaavilla sähkön- ja lämmön yhteistuotantolaitoksilla verrattuna perusskenaarioon, sillä korkeampi teollisuuden sähkön kysyntä nostaa sähkön hintaa ja siten CHP-tuotanto pysyy kilpailukykyisenä

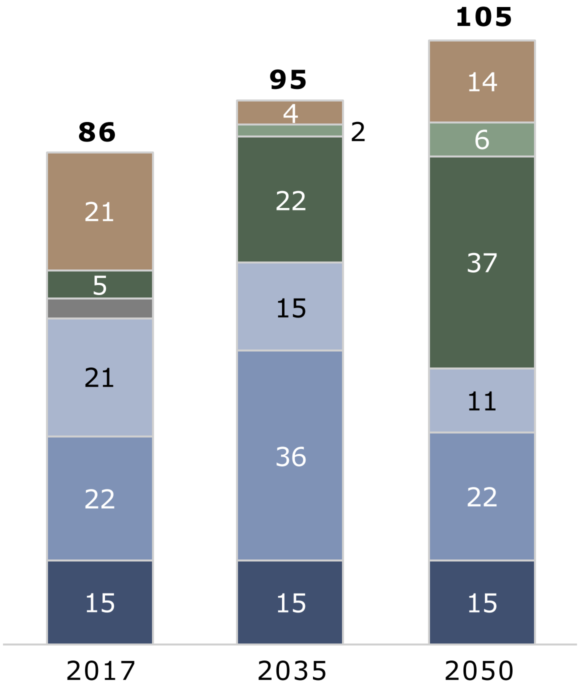
Ydinvoimatuotanto kasvaa merkittävästi

- Ydinvoiman tuotanto kaksinkertaistuu vuoteen 2035 mennessä, sillä kaksi uutta ydinvoimalaa, Olkiluoto 3 ja Hanhikivi 1, liittyvät verkkoon ja aloittavat kaupallisen tuotannon ja Loviisan voimalaitosten käyttöikää pidennetään vuoden 2035 yli. Lisäksi Olkiluoto 1 & 2 elinaikoja pidennetään tai ne korvataan uusilla laitoksilla vuoteen 2050 mennessä.

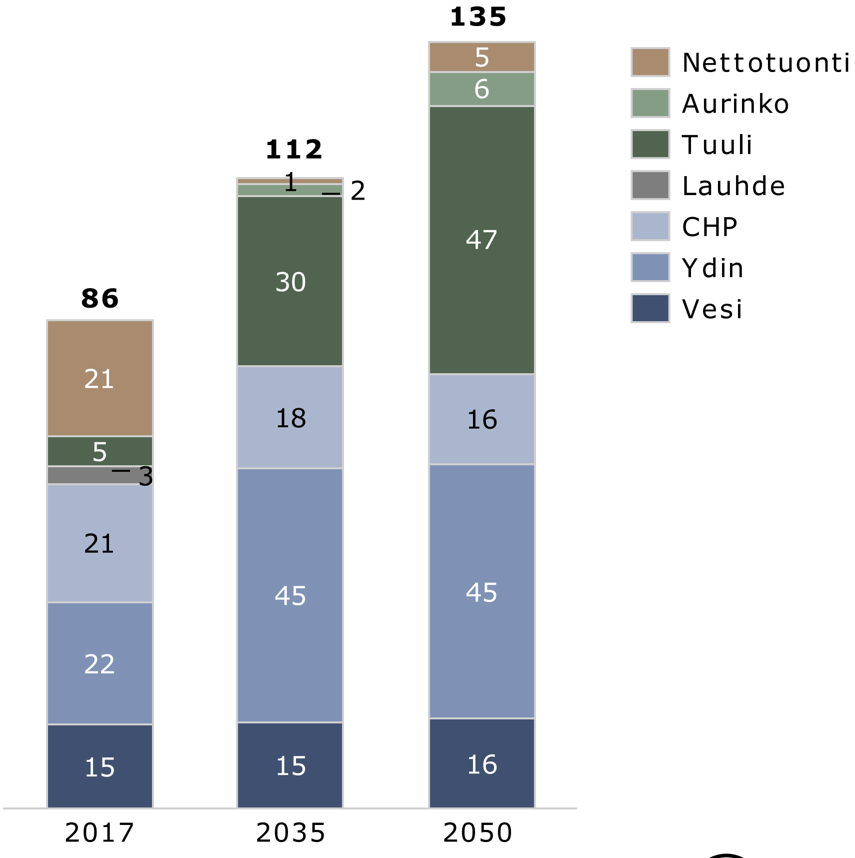
Uusiutuvilla tuotetaan valtaosa sähköstä 2050, etenkin tuulivoiman osuus kasvaa

- Tuulivoima saavuttaa 22TWh tuotannon vuonna 2035 ja 37TWh vuonna 2050, mistä merituulivoima kattaa liki 20% vuonna 2035 ja noin 30% vuonna 2050 suuremman kapasiteettikertoimen ansiosta

SÄHKÖN HANKINTA PERUSSKENAARIOSSA
TWh



SÄHKÖN HANKINTA VÄHÄHIILISKENAARIOSSA
TWh



Sähkön ja lämmön yhteistuotannon osuus kaukolämmön tuotannosta pysyy merkittävänä vähähiilisessä skenaariossa

Polttoaineiden osuus kaukolämmön tuotannossa vähenee

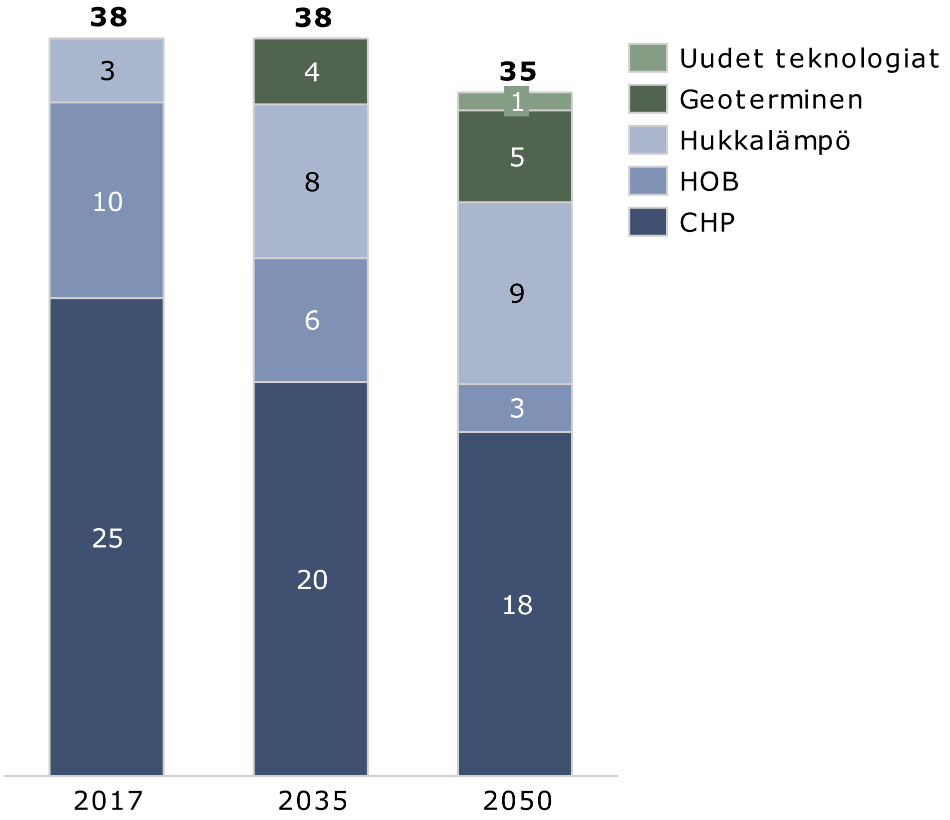
- Verrattuna kaukolämmön tuotantoon perusskenaariossa, sähkön ja lämmön yhteistuotannon osuus säilyy selvästi suurempana, mutta laskee silti vuoden 2017 n. 65%:sta noin 50%:iin vuoteen 2050 mennessä. Tämä johtuu siitä, että korkea sähkön kysyntä ajaa korkeampaan sähkön hintaan, mahdollistaen nykyisen CHP-kapasiteetin korvausinvestoinnit vastaavilla yhteistuotantovoimalaitoksilla
- CHP-laitokset optimoivat sähkön ja lämmön tuotannon suhdetta ja korkeiden sähkön hintojen vuoksi sähköntuotantoa lisätään, myös lauhdetuotantona
- Lämpölaitosten määrä vähenee, sillä ne korvataan pääosin vaihtoehtoisilla energialähteillä ja vuoteen 2050 mennessä lämmön erillistuotantoa on vain noin 3TWh jäljellä pienten verkkojen ja huipputehokapasiteetin tuotannossa. CHP:n ja lämpölaitosten tuotannon välinen suhde on skenaarion suurin epävarmuus. Se riippuu paljon kaukolämpöverkkojen kyvystä mm. varastoida ja jakaa lämpöä, ja erillistuotannon osuus voi olla suurempi esimerkiksi kylminä vuosina

Maalämmön ja hukkalämmön käyttö kasvaa, korvaten enimmäkseen erillistuotantoa

- Hukkalämmön hyödyntäminen kasvaa merkittävästi vuoden 2017 n. 3TWh:n tasosta n. 8 TWh:iin vuoteen 2035 mennessä, sillä sitä aletaan hyödyntää helpoiten saatavilla olevista lähteistä kuten datakeskuksista. Tämän jälkeen kasvu hidastuu korkeampien sähkön hintojen vuoksi ja saavuttaa lopulta n. 9TWh tason vuonna 2050. Tällöin hukkalämpöä hyödynnetään n. 3TWh vähemmän kuin perusskenaariossa. Sähkökattiloiden osuutta ei ole arvioitu erikseen
- Geotermisten teknologioiden oletetaan tulevan markkinoille ja näistä pääasiassa hyödynnetään korkeamman COP:in syväporausratkaisuja korkeampien sähkön hintojen vuoksi, yhteensä 4TWh vuonna 2035 ja 5TWh vuonna 2050, jolloin geotermistä lämpöä hyödynnetään n. 3TWh vähemmän kuin perusskenaariossa.
- Uusien teknologioiden oletetaan saavuttavan 1TWh tuotanto vuonna 2050, mikä voi teknologisesta kehityksestä riippuen olla huomattavasti korkeampi

KAUKOLÄMMÖN TUOTANTOSKENAARIO VÄHÄHIILISKENAARIOSSA 2017-2050

TWh



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Polttoaineiden kokonaiskulutus laskee, mutta puupohjaisten polttoaineiden kulutus kasvaa vähähiiliskenaariossa

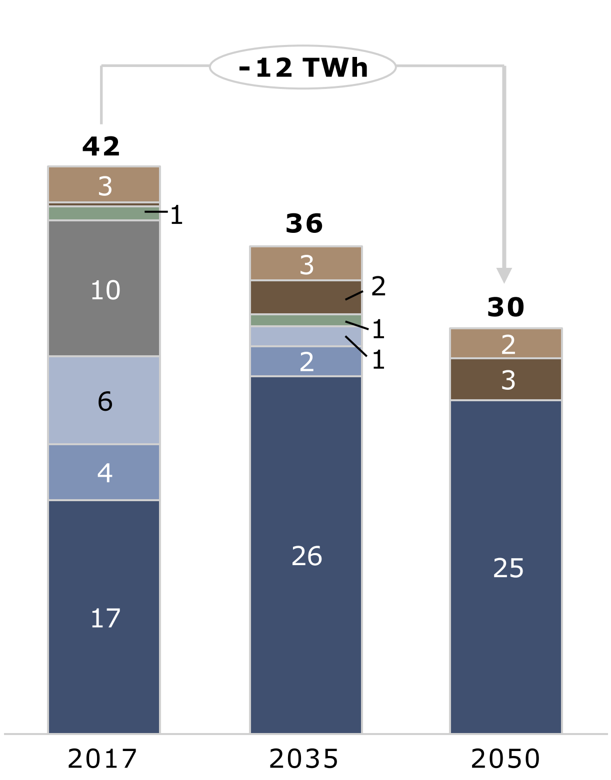
Polttoaineen kulutus laskee

- Sähkön ja kaukolämmön tuotannossa, ml. teollisuuden CHP-tuotanto, käytetyn polttoaineen kulutuksen arvioidaan vähenevän noin 26TWh vuoteen 2035 mennessä ja noin 38TWh vuoteen 2050 mennessä.
- Perusskenaarion verrattuna CHP tuotantoa on enemmän, mikä johtaa korkeampaan polttoainekäyttöön, mutta kokonaisuudessaan polttoaineiden käyttö on silti laskussa sillä myös CHP-tuotantoa korvataan polttoon perustumattomilla tuotantoratkaisuilla

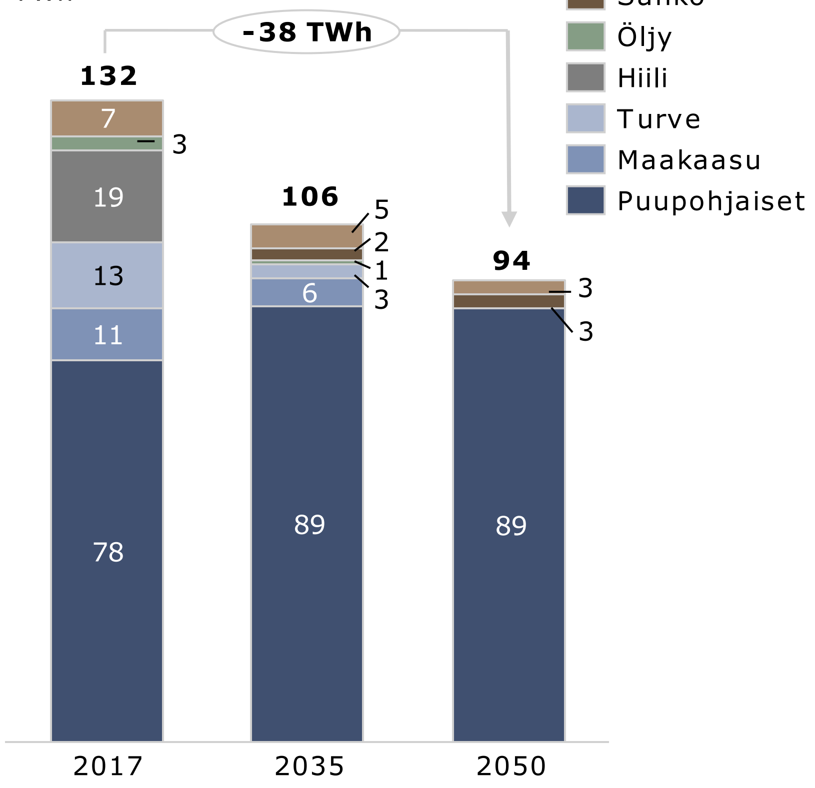
Puupohjaisten polttoaineiden kulutus kasvaa

- Puupohjaisten polttoaineiden kulutus kasvaa 11TWh vuoteen 2035 mennessä, saavuttaen liki 90TWh tason pysyen siinä vuoteen 2050
- Suurin osa puupohjaisten polttoaineiden käytön kasvusta johtuu fossiilisten polttoaineiden korvaamisesta kaukolämmön CHP-tuotannossa vuoteen 2035 mennessä, kun taas mustalipeän käytön odotetaan pysyvän nykyisellä tasolla teollisuus-CHP:ssa
- Fossiilisten polttoaineiden käyttö vähenee samalla tavalla kuin perusskenaariossa: kivihiilen käyttö lopetetaan asteittain enne vuotta 2035 ja nykyistä kapasiteettia poistuu käytöstä, mikä johtaa kaasun ja öljyn käytön vähentymiseen.

KAUKOLÄMMÖN TUOTANNON POLTTOAINEEN KULUTUS VÄHÄHIILISKENAARIOSSA
TWh



SÄHKÖN JA KAUKOLÄMMÖN POLTTOAINEEN KULUTUS VÄHÄHIILISKENAARIOSSA
TWh



Sähkön ja kaukolämmön tuotanto saavuttavat lähestulkoon päästöttömyyden molemmissa skenaarioissa

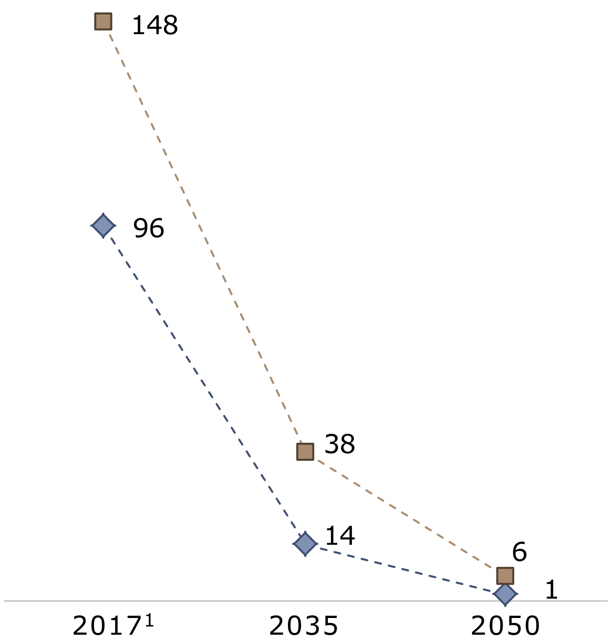
Päästöt vähenevät merkittävästi

- Kokonaisuudessaan polttoaineen kulutus laskee ja fossiiliset polttoaineet korvataan puhtaammilla vaihtoehdoilla sekä kaukolämmössä että energiantuotannossa, mikä johtaa merkittävään laskuun molempien skenaarioiden päästöissä
- Päästökertoimet vähähiilisessä skenaariossa ovat hiukan alhaisemmat kuin perusskenaariossa johtuen korkeammista tuotantomääristä uusiutuvilla energialähteillä verrattuna fossiilisiin polttoaineisiin

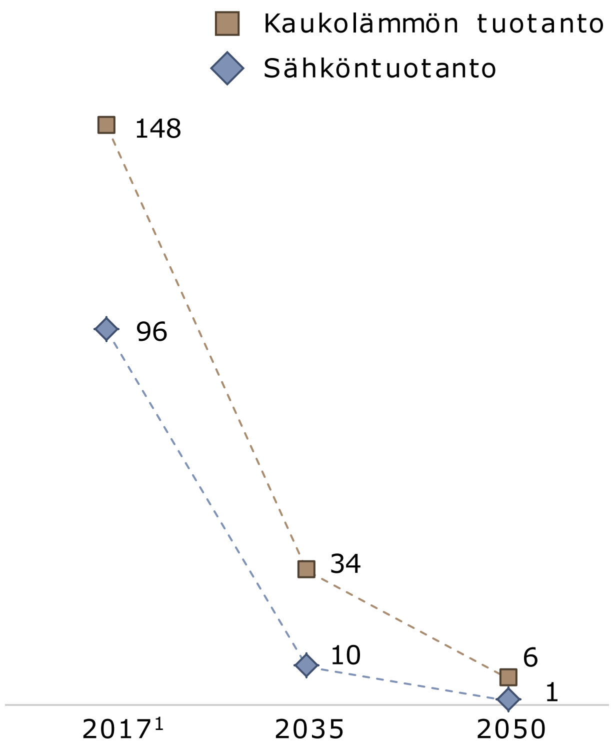
Päästöt hyvin alhaiset jo vuonna 2035

- Päästöjen lasku vuoteen 2035 mennessä johtuu pääasiassa hiilen käytön lopettamisesta, mutta myös nykyisen maakaasu- ja öljykapasiteetin poistuminen sekä turpeen käytön vähentyminen vaikuttavat merkittävästi. Jäljellä olevat päästöt syntyvät pääasiassa maakaasun ja turpeen käytöstä
- Vuonna 2050 päästöjä syntyy enää vain jäte- ja sekapolttoaineiden tuotannosta. Kiertotalouden edistyminen vaikuttaa näiden päästöjen muodostumiseen. Sähkön ja kaukolämmön tuotanto ovat lähes päästöttömiä.

PERUSSKENAARIO SÄHKÖN JA KAUKOLÄMMÖN TUOTANNON PÄÄSTÖKERTOIMET
kg CO2/MWh

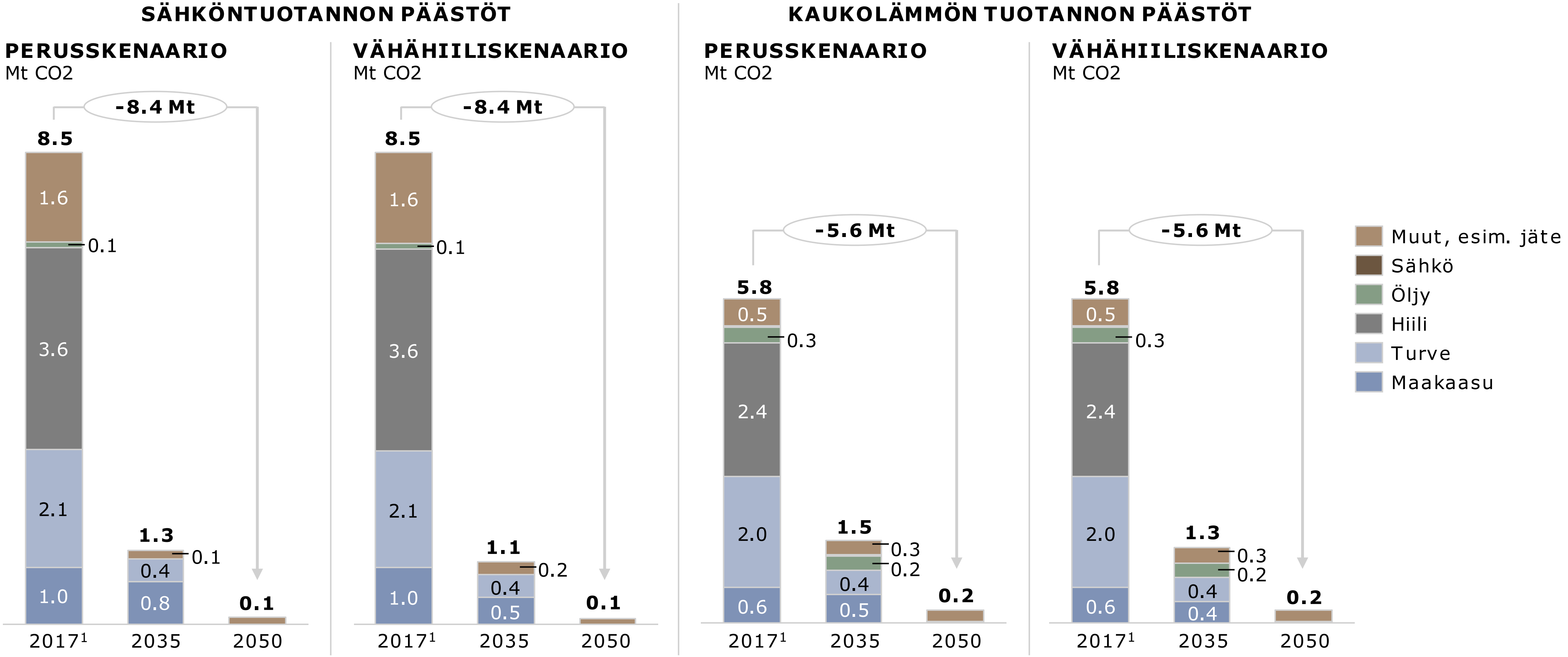


VÄHÄHIILISKENAARIO SÄHKÖN JA KAUKOLÄMMÖN TUOTANNON PÄÄSTÖKERTOIMET
kg CO2/MWh



1: Energiateollisuus (2018), päästökertoimet vuonna 2017
Huomio: Päästöt kotimaiselle sähköntuotannolle, päästöt sähkön ja kaukolämmön yhteistuotannosta on jyvitetty käyttäen hyödynjakomenetelmää

Sähkön ja kaukolämmön tuotanto saavuttavat lähestulkoon päästöttömyyden molemmissa skenaarioissa



1 Tilastokeskus, Lämmön ja sähkön tuotanto, energialähteet ja hiilidioksidipäästöt 2017
Huomio: Päästöt kotimaiselle sähköntuotannolle, päästöt sähkön ja kaukolämmön yhteistuotannosta on jyvitetty käyttäen hyödynjakomenetelmää

Executive summary

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A substantial increase in electricity generation capacity is needed as a result of the low carbon roadmaps of energy-intensive industries

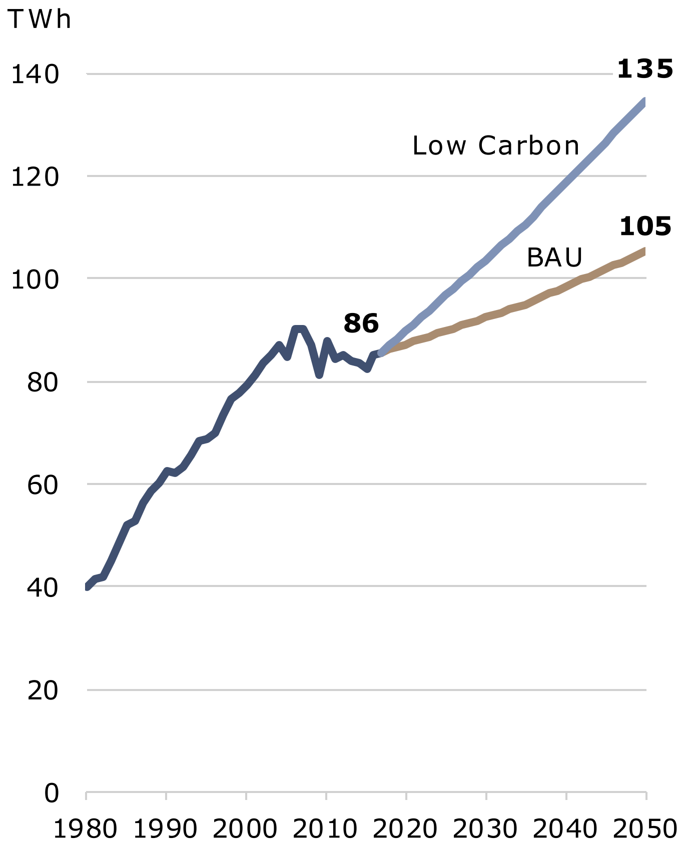
- Decarbonisation of industries is likely to increase electricity demand in Finland significantly compared to business-as-usual trajectory
  - The scale and timing of the investments especially in electrification of process heating and power-to-hydrogen has a drastic impact on Finnish electricity demand by 2035 and even more by 2050
  - Increased industrial demand in the Low carbon scenario offers significant additional demand-side flexibility
  - All sources of demand-side flexibility should be developed actively to enable a significant increase in intermittent production
- Substantial investments are required in electricity generation due to the massive increase in electricity demand
  - Compared to a business-as-usual scenario, investments in new capacity are needed at a clearly faster pace
  - Costs of clean electricity production have plummeted during the past decade and additional cost decrease is projected
  - For investments to happen in the timescale required and in a cost-efficient way, reliable investment signals are needed together with efficiently functioning electricity markets
- Transmission network needs to be strengthened within Finland and across borders to accommodate increased electricity flows and balancing of the Finnish system in different weather conditions
  - Significant increase in demand and in weather-dependent wind generation require very strong interconnection and efficient cross-border markets so that the flexibility of the wider markets can be utilised to balance the Finnish system
  - Demand concentrates in larger cities due to urbanization and electrification of transport and heat, and at industrial sites
  - Transmission grid investments have long lead times compared to demand/supply side investments hence flexibility measures should be considered as an alternative to cope with potential bottlenecks

District heating and combined heat and power production play a significant role in a low carbon future

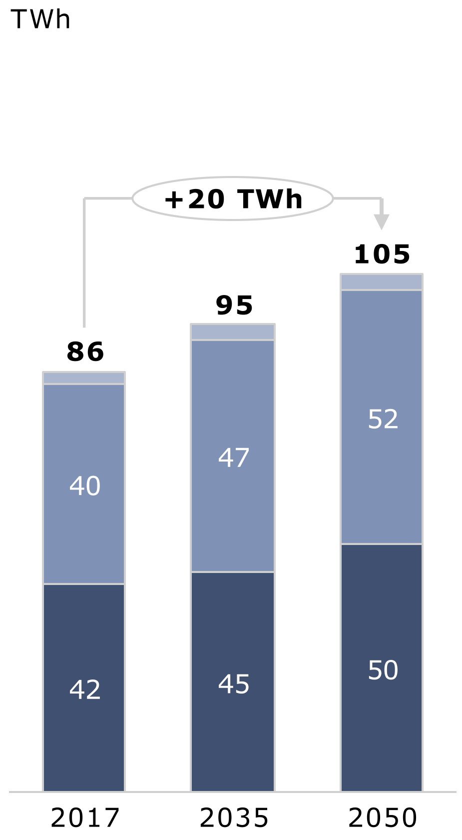
- As a result of significant increase in electricity demand in the Low carbon scenario the role of CHP capacity in district heat production is emphasised to ensure security of supply in the power system
  - This has a direct impact on the expected consumption of biomass, which dominates the fuel mix in the business-as-usual and Low carbon scenarios
  - Heat pumps and geothermal heat are expected to play a clearly larger role in the future in district heat production
  - Geothermal heat still has uncertainties with regards to the technical and commercial potential, but is assumed to reach market maturity by 2035 in the scenarios
  - Possible new heat technologies such as SMR (small modular reactors) or CSP (Concentrated Solar Power) are also likely to be technically available in the future
- District heating systems offer sources of flexibility for the energy system in several ways
  - CHP production provides flexibility as heat demand correlates very well with the electricity demand profile in different timescales seasonally and within day
  - Heat pumps and electric boilers can utilise low electricity prices and provide demand-side flexibility
  - This flexibility is enhanced by district heating storages
  - Smart energy control systems and service platforms enable better utilization of, e.g., customers' own energy production and demand-side response, which can support the whole energy system
- Gas use in power generation to decline as current capacity retires. Gas remains as a fuel used in peak load heat production. Declining gas demand in power generation is partly offset by minor demand growth projected in industry roadmaps.

The Low carbon pathway is likely to increase industrial electricity demand in Finland significantly compared to business-as-usual trajectory

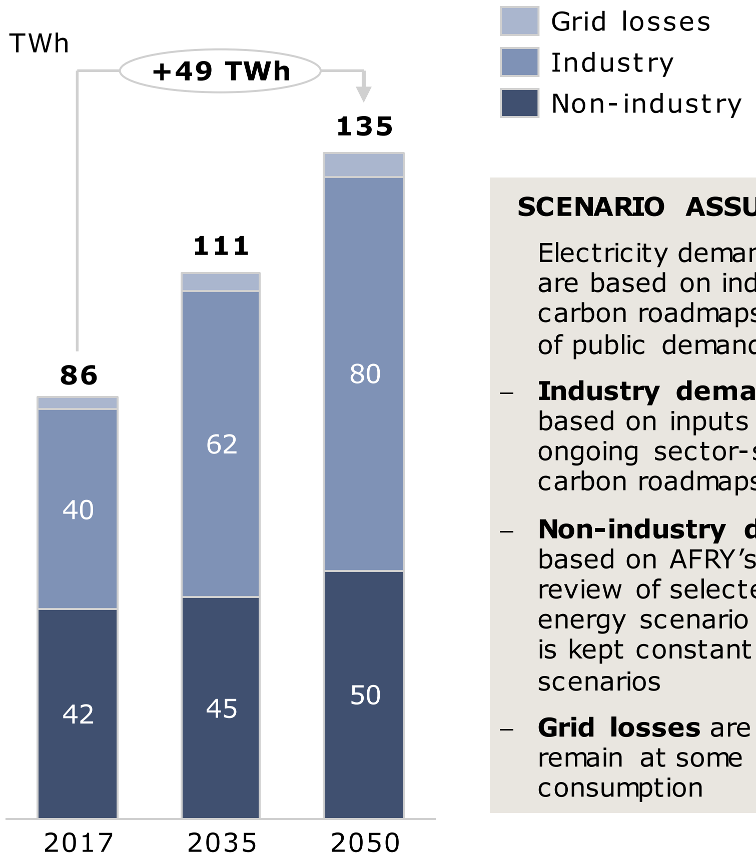
POSSIBLE DEVELOPMENT TRAJECTORIES FOR ELECTRICITY DEMAND IN FINLAND



BAU SCENARIO



LOW CARBON SCENARIO



SCENARIO ASSUMPTIONS

Electricity demand scenarios are based on industry Low carbon roadmaps and review of public demand projections

- **Industry demand** is mostly based on inputs from parallel ongoing sector-specific Low carbon roadmaps
- **Non-industry demand** is based on AFRY's high level review of selected recent energy scenario studies and is kept constant in both scenarios
- **Grid losses** are assumed to remain at some 3% of consumption

AFRY analysis

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Increasing generation with renewables, especially wind, and nuclear answer to the increased electricity demand in the Low carbon scenario

LOW CARBON SCENARIO COMMENTS

Only modest decline in CHP capacity

- Compared to the BAU scenario, more of the existing CHP fleet is replaced as higher industrial electricity demand increases electricity prices and thus CHP production remains competitive

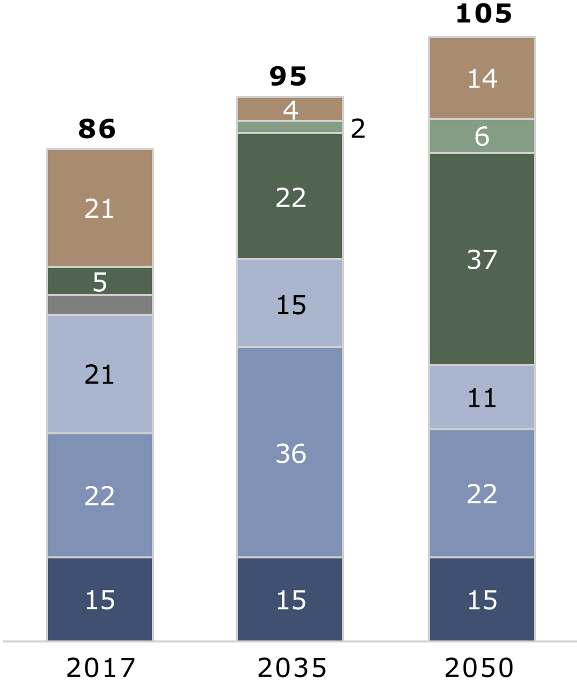
Nuclear capacity increases significantly

- Nuclear generation doubles up to 45TWh by 2035 as two new nuclear plants, Olkiluoto 3 and Hanhikivi 1 come online, and the lifetime of Loviisa plants are extended over 2035. Lifetime of Olkiluoto 1 & 2 are also extended or replaced by a new plant by 2050

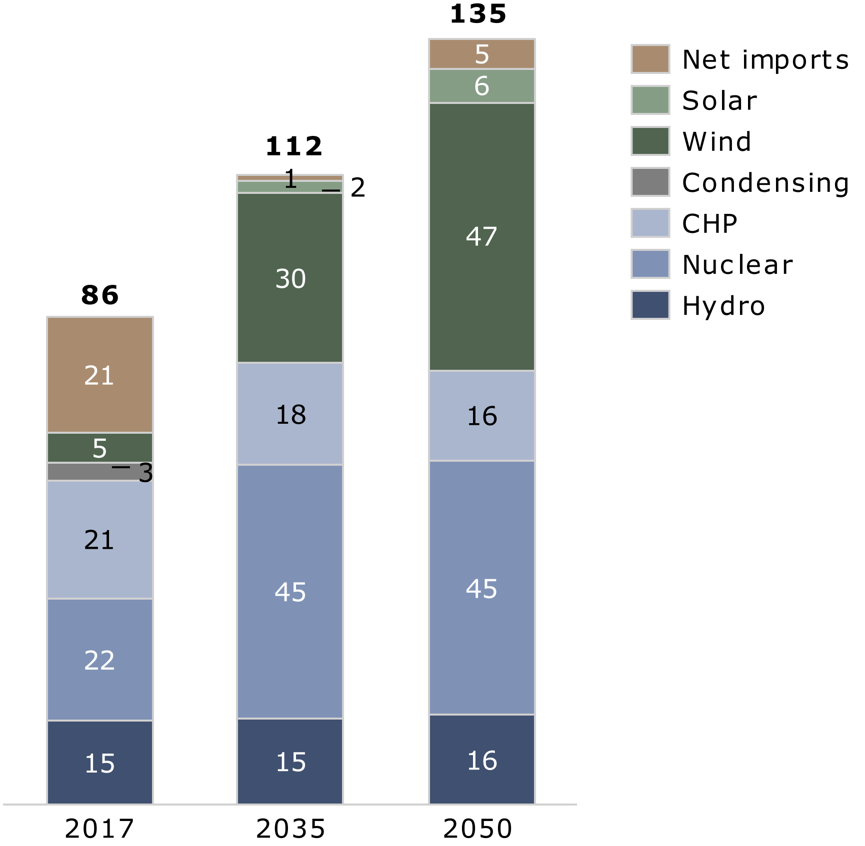
Large scale penetration of RES – especially wind power including offshore

- Wind power is 22TWh in 2035 and 37TWh in 2050, of which around 20% in 2035 and 30% in 2050 accounted for offshore wind power with higher load factor

ELECTRICITY SUPPLY IN THE BAU SCENARIO
TWh



ELECTRICITY SUPPLY IN THE LOW CARBON SCENARIO
TWh



The share of CHP production remains significant in the Low Carbon scenario

District heat produced with fuels declines

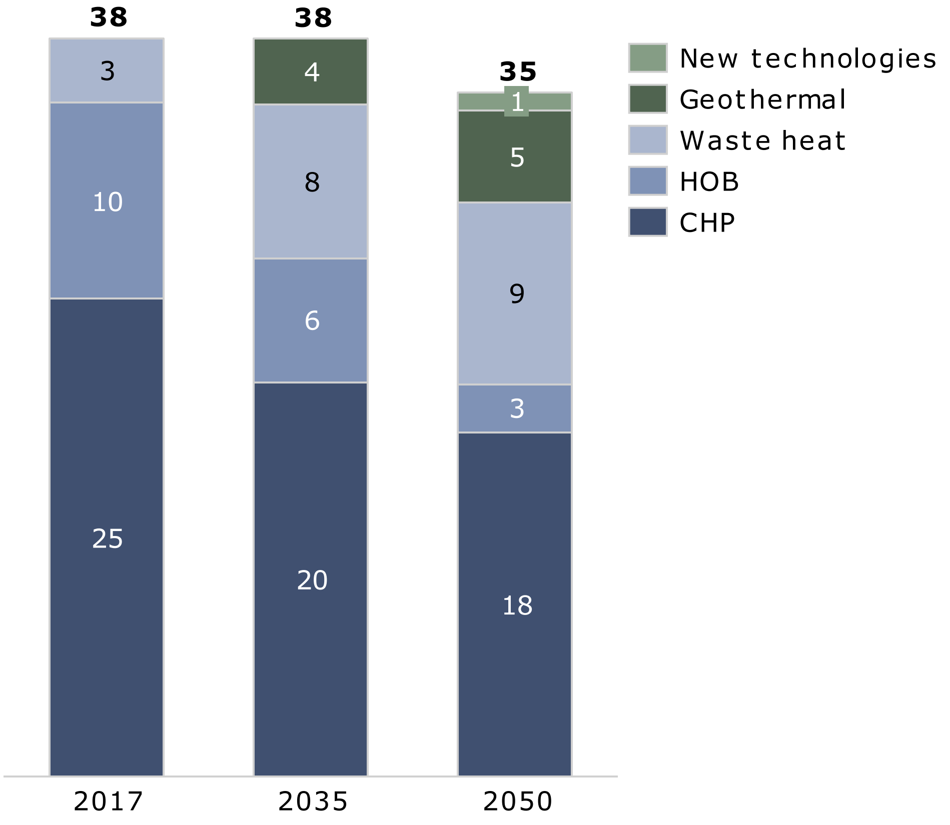
- Compared to the DH supply in BAU scenario, the share of CHP supply remains clearly higher but still decreases from 65% in 2017 to around 50% in 2050. This is due to CHP district heating capacity declines less than in the BAU scenario as most of the existing CHP plants are assumed to be replaced due to high electricity demand increasing prices, making the replace investments feasible
- CHP plants also optimise electricity and heat production and due to high electricity demand the ratio between electricity and heat produced is increased slightly from the current situation as more condensing power is produced
- HOBs see a decrease as they are replaced with alternative energy sources and by 2050 only 3TWh of HOB production remains to supply small distant networks and peak capacity when required. The ratio between CHP and HOB supply is the main uncertainty in the scenario. It depends a lot on the DH networks storage and distribution capabilities to meet the heat demand at all times and e.g. due to cold winters the share of HOB production can be higher

Geothermal and waste heat increase replacing mostly HOBs

- Waste heat amounts increases from the 2017 level of around 3TWh to 8TWh in 2035 as most easily available sources such as data centers are utilised, after which the growth decreases due to higher electricity prices and eventually reaches 9TWh in 2050. Waste heat utilisation is 3TWh less compared to the BAU scenario in 2050. Share of electric boilers has not been estimated separately.
- Geothermal heat is assumed to reach maturity and mainly the deep borehole solutions with higher COP are exploited due to higher electricity prices. This leads to DH production of 4TWh in 2035 and 5TWh in 2050, of which the latter is 3TWh less than in the BAU scenario
- New technologies are assumed to constitute 1TWh of the demand in 2050, which depending on the technological development can be significantly higher

DISTRICT HEATING SUPPLY SCENARIO IN LOW-CARBON SCENARIO FOR 2017-2050

TWh



Fuel consumption declines but wood based fuels see increase as fossil fuel CHPs are converted or replaced in the Low Carbon scenario

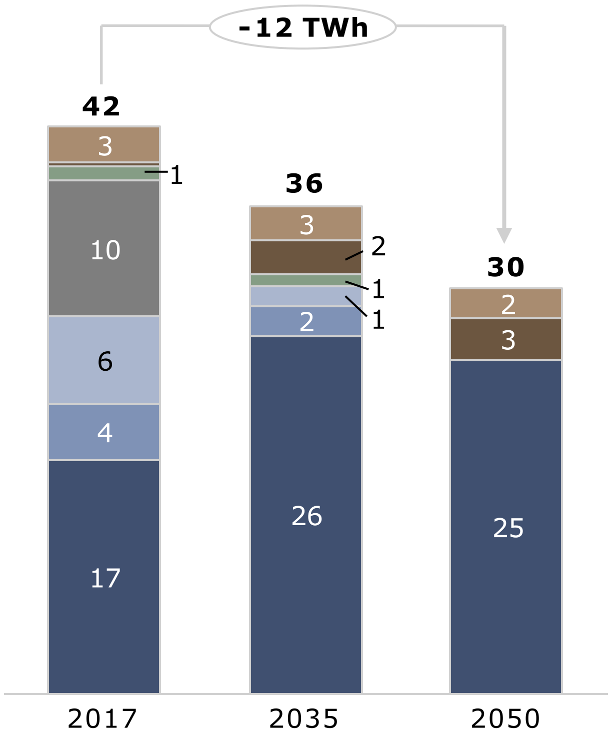
Fuel consumption declines

- Fuel consumption used for district heating and power production, including CHP production in industries, is estimated to decline by some 26TWh by 2035 and 38TWh by 2050, of which respectively 6TWh and 12TWh are due to decrease in district heat fuel use
- Compared to BAU scenario there is more CHP production leading to using fuels but overall trend is still decreasing as some of the CHPs are replaced with non-fuel based heat and power production

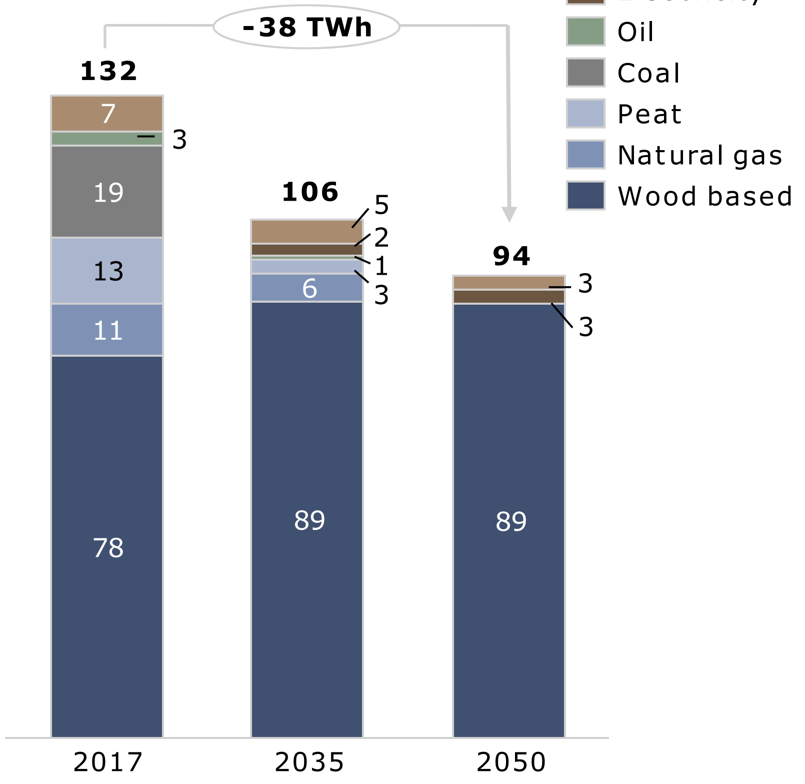
Wood based fuels see increase

- In total wood based fuel use increases by some 11TWh by 2035 reaching nearly 90TWh, after which it stays at the same level
- Most of the increase in wood based fuels is due to fossil fueled CHPs in district heating converted to use increased share of wood based fuels or replaced with bio-CHPs by 2035, whereas black liquor use in pulp industry is expected to remain at current levels
- Fossil fuel use declines the same way as in the BAU scenario as coal use is phased out before 2035 and existing capacities are retired leading to decrease in gas and oil use

DISTRICT HEATING FUEL CONSUMPTION IN LOW CARBON SCENARIO
TWh



POWER AND DISTRICT HEATING FUEL CONSUMPTION IN LOW CARBON SCENARIO
TWh



Power and district heating production reach nearly carbon-neutrality as wood based fuels and cleaner alternatives replace fossil fuels and peat

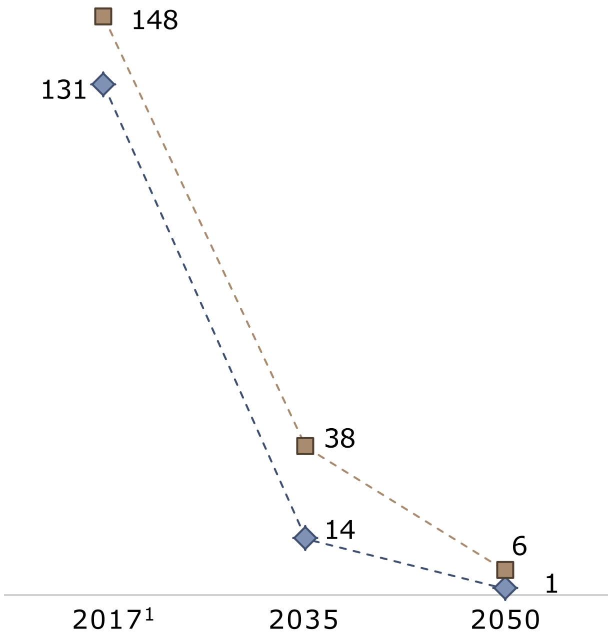
Emissions decrease significantly in both scenarios

- As overall fuel consumption declines and fossil fuels are replaced with cleaner alternatives both in district heating and power production, the emissions see a significant decrease in both scenarios
- Emission factors in the Low Carbon scenario are slightly lower than in the BAU scenario due to more renewable production in comparison to fossil fuel production

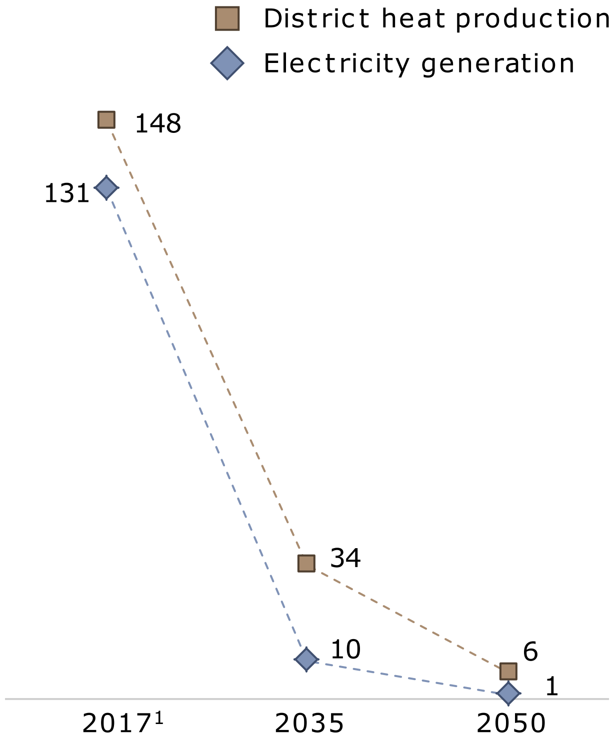
Emissions low already in 2035, only some in 2050

- The decrease by 2035 is mainly due to the phase-out of coal use but also the retirement of existing gas and oil capacities, as well as reduced peat use contribute significantly to the decrease. Remaining emissions are mainly from gas and peat use
- By 2050 there is only some production left with waste and mixed fuels that cause emissions, which overall are in very low level and electricity generation as well as district heat production reach nearly carbon-neutrality

BAU SCENARIO
EMISSION FACTORS OF ELECTRICITY AND DISTRICT HEAT PRODUCTION
kg CO_2/MWh

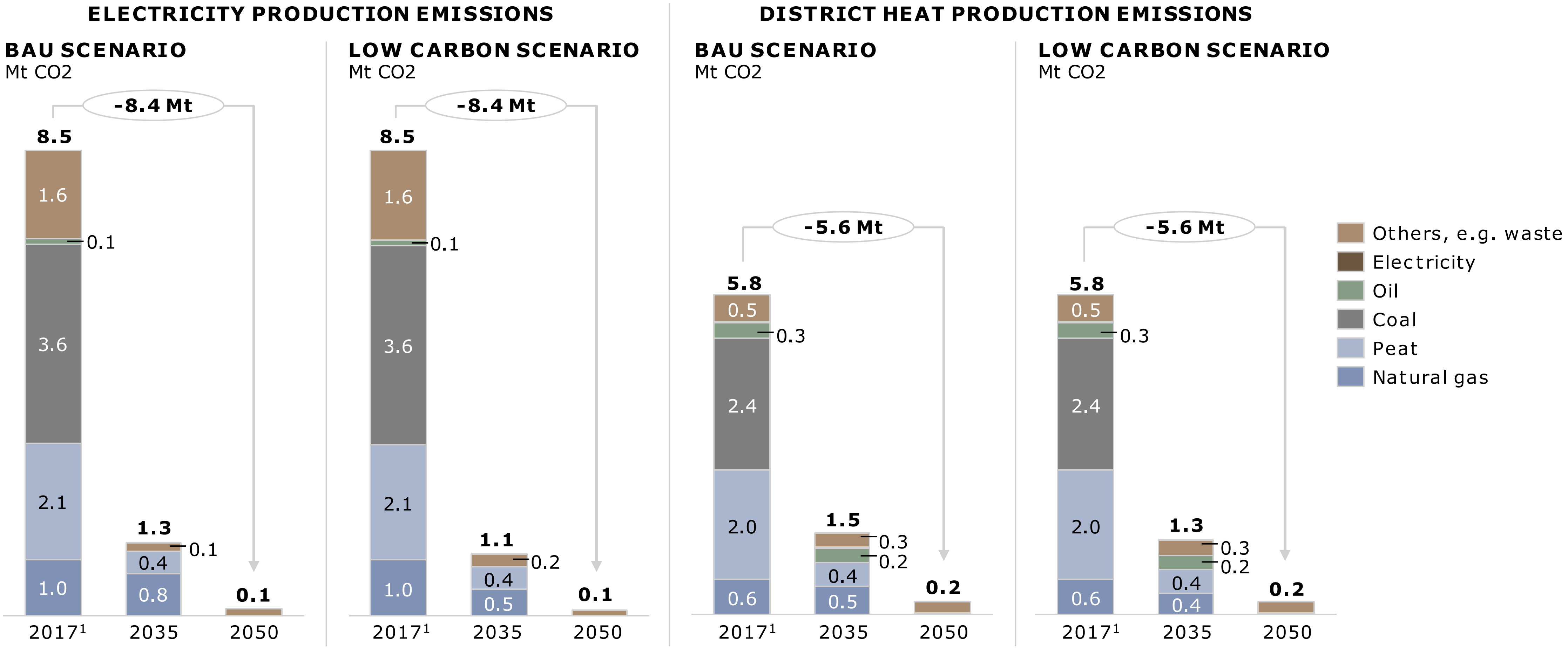


LOW CARBON SCENARIO
EMISSION FACTORS OF ELECTRICITY AND DISTRICT HEAT PRODUCTION
kg CO_2/MWh



1 Statistics Finland (electricity generation emissions in 2017), Finnish Energy (emission factor of district heat production in 2017)
Note: Emissions for domestic electricity generation, emissions from cogeneration allocated using the benefit allocation method (hyödynjakomenetelmä)

Power and district heating production reach nearly carbon-neutrality as wood based fuels and cleaner alternatives replace fossil fuels and peat



1 Statistics Finland, Heat and power production, energy sources and carbon dioxide emissions 2017
Note: Emissions for domestic electricity generation, emissions from cogeneration allocated using the benefit allocation method (hyödynjakomenetelmä)

Introduction

The government programme is looking for answers from energy-intensive industries to fulfil carbon neutrality target by 2035

BACKGROUND AND OBJECTIVES

- The current government programme introduced a carbon neutrality target by 2035, which is clearly more ambitious than the previous carbon emission reduction targets
- In addition, the government programme aims for Finland to become carbon negative soon after 2035
- It is also stated that sector-specific Low carbon roadmaps will be created together with industry operators that will be brought in line with the new climate actions
- Work on sector-specific Low carbon roadmaps is coordinated by the Ministry of Economic Affairs and Employment to ensure that they are compatible

SCOPE AND APPROACH

- The scope of this study is as follows:
  - To create business-as-usual and Low carbon scenarios for the demand and supply of electricity, district heating, including demand for gas
  - To identify the necessary actions so that the Low carbon scenario can be realised, including key risks and uncertainties
  - To estimate the development of carbon emissions in the different scenarios
  - To evaluate the impact of the Low carbon scenario on the electricity system in terms of demand and supply balance
  - To create an overview of the current state and anticipated development of different technologies for electricity and heat generation, including different flexibility and storage technologies and solutions
- Inputs for the scenarios are based on the Low carbon roadmaps of energy-intensive industries[1], public sources and AFRY analysis, focusing on the years 2035 and 2050

1. The Chemical Industry Federation of Finland, Technology Industries of Finland, Finnish Forest Industries

Low carbon energy technologies

Solutions for clean energy sector have developed rapidly and are versatile in their characteristics, complementing one another

INTRODUCTION TO KEY SOLUTIONS

- This section describes the main technological solutions for carbon-neutral energy sector in Finland.
- The technologies have been divided into production, transmission and flexibility of electricity and production and flexibility of heat. Gas sector is included into electricity and heat for relevant parts.
- Electricity and heat sectors are not developing independently but they have interactions. For example heating solutions might impact electricity grid or electricity generation capacity.
- The main technologies are described on high level. Indication of technological maturity and cost level of the related energy or capacity are given in today's situation for each technology. Indication of the techno-economic potential is presented for the Low carbon scenario in Finland.

INDICATORS

MATURITY

Early development — Mature

POTENTIAL

\+ ++ +++

Limited — Significant

COST

€ €€ €€€

Very competitive — Expensive

MAIN LOW CARBON TECHNOLOGIES ANALYSED IN THIS STUDY

ELECTRICITY

PRODUCTION

- Wind power; onshore and offshore
- Nuclear power; existing and new capacity
- Bio-CHP; district heating and industrial
- Solar PV
- Gas-fired generation

TRANSMISSION

- Interconnections

FLEXIBILITY

- Demand response; industrial, heating and residential sectors
- Electricity storages; batteries, pumped hydro and power-to-gas

HEAT

PRODUCTION

- Bio-CHP
- Bio-HOB
- Heat pumps; industrial waste heat, ambient heat
- Geothermal; mid-deep and deep
- Electric boilers

FLEXIBILITY

- Demand response
- Heat storages

LOW CARBON ENERGY TECHNOLOGIES

Electricity generation and transmission

AFRY
ÅF PÖYRY

Wind, hydro, bio-CHP and nuclear expected to provide the bulk of low carbon electricity

Technology	LCOE[1] today (Finland)	Expected cost development	Techno-economic potential[2]	Remarks
Wind, onshore	30-40 €/MWh	↘	+++	– Potential locations available across the country – Adequacy of transmission grid is crucial – Intermittency creates a need for additional dispatchable capacity
Wind, offshore	80-120 €/MWh	↘	++	– Technology develops fast
Bio-CHP, district heat	50-60 €/MWh	↗	++	– Availability and sustainability of biomass limit the potential – Increasing demand expected to increase biomass prices
Nuclear, refurbishment of the existing	20-30 €/MWh	→	+++	– Cost efficient – Significant contribution to security of supply
Nuclear, new	60-80 €/MWh	→	?	– High political uncertainty hinders development
Solar PV	80-110 €/MWh	↘	++	– Strong seasonality limits the overall potential – Economies of scale assumed to decrease cost
Hydro	-	-	-	– Environmental restrictions limit opportunities to build new capacity or increase the ability to adjust output of the existing plants
Gas-fired generation with CCS/CCU	?	↘	+	– Limited availability of biogas and high cost of synthetic gas – CCS technology is still in development phase
Interconnectors	1.2 €/MW/km	→	+	– Increased competition to utilize the flexibility of Nordic hydro power – Internal transmission network adequacy for clean energy utilisation

1 Levelized cost of energy
2 In the Low carbon scenario which is described later in the report
Sources: AFRY (Pöyry and ÅF), other sources mentioned in the technology description later in the report

AFRY
ÅF PÖYRY

Wind power expected to become the dominant source of clean electricity

ONSHORE WIND POWER INCREASES ON MERCHANT BASIS

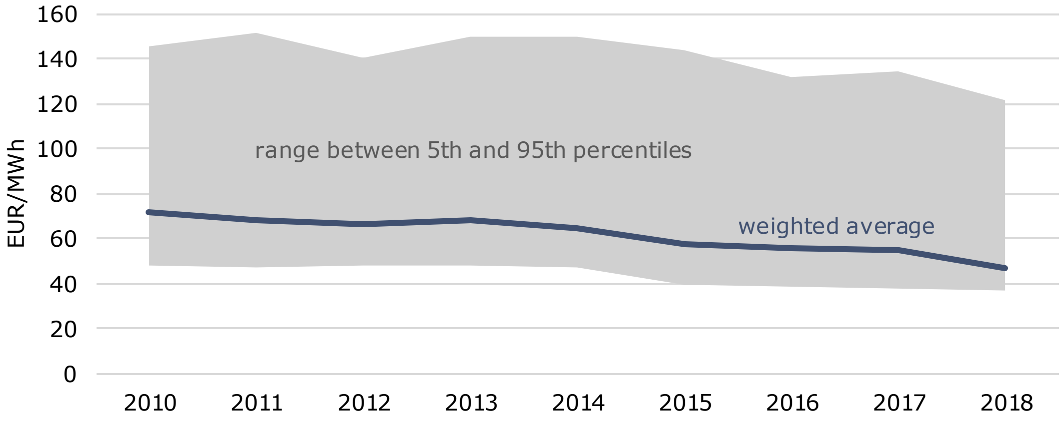
Wind power technology has developed considerably during the last decade. Higher hubs and longer blades have raised generator capacities and capacity factors. Larger size enables more continuous electricity generation due to stronger and more stable airflow at higher heights.

The Finnish wind power capacity increased as a consequence of feed-in-tariffs introduced in 2011. A new auction for renewable energy in 2019 resulted in 1.4TWh with an average premium of 2.5 €/MWh on top of the reference electricity market price. New wind power investments are announced frequently and they carried out without subsidies on a merchant basis, often with a power purchase agreement (PPA).

Wind power production in 2019 was 6.0TWh which corresponds to 9% of the Finnish electricity production. Wind power is expected to become the dominant source of new domestic electricity generation capacity.

Adequate transmission capacity is central to wind power increase to avoid undue curtailment of production due to network congestions. The majority of wind farms are located in Western and Northern Finland. Possible interference effects of the wind blades with Defence Forces' radar equipment currently limit the opportunities to construct wind power also in Eastern and Southern Finland.

Global onshore wind LCOE development[1]



BENEFITS	LIMITATIONS
– Mature technology	– Intermittency
– Low generation costs	– Challenges with construction permissions in South/East Finland
– Production correlates with demand (production is typically higher in winter compared to summer)	– Need to strengthen transmission networks
	– Cannibalization impacts profitability

Maturity ●	Potential +++	Cost €

1 IRENA, 2019

AFRY ÅF PÖYRY

Offshore wind power enjoys high capacity factors and relatively stable renewable generation

INCREASED DEVELOPMENT IN NORTH AND BALTIC SEA

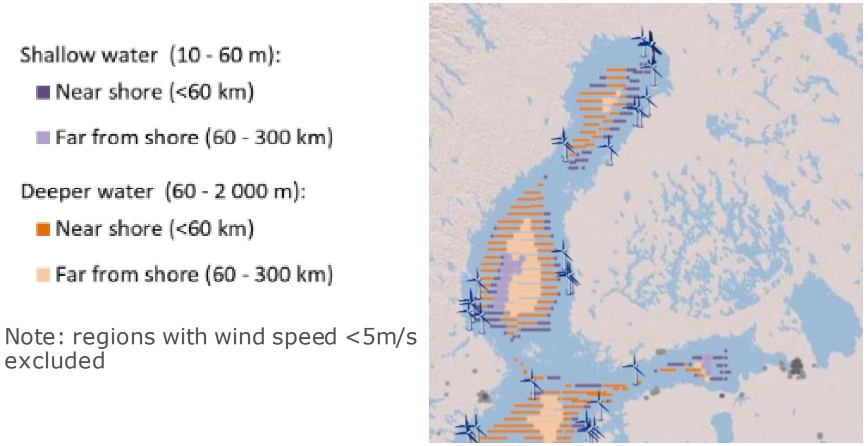
Offshore wind power enjoys relatively stable wind conditions and hence steadier output compared to onshore wind power or solar power. New offshore wind projects can reach capacity factors of over 50%. The output of the large offshore turbines fluctuate within a narrower band compared to for example solar PV generation due to large physical size which makes the generation less sensitive to wind speed variation.

The LCOE of offshore wind has decreased over 30% during the past five years and it is expected that there is substantial potential for the cost to decrease. Base construction, network connection and maintenance costs of off-shore wind are higher compared to onshore wind.

Global offshore wind capacity reached 24GW in 2018, majority installed in Europe. Off-shore wind is feasible in locations where the sea depth is relatively shallow like in North Sea and Baltic Sea. Finland's first offshore wind power park was commissioned in Tahkoluoto in 2017.

The offshore wind capacity in Finland is currently less than 0.1GW. Estimations for offshore wind potential in Finland range between 15TWh to 40TWh. Wider deployment of offshore wind on the Finnish coast will take time due to higher costs compared to many other technologies. The government has stated it will lower property tax for off-shore wind and remove undue administrative burden for off-shore wind development.

TECHNICAL POTENTIAL FOR OFFSHORE WIND[1]



Note: regions with wind speed <5m/s excluded

BENEFITS	LIMITATIONS
– Technology costs expected to decrease further	– High installation and grid connection costs impacted also by icy conditions
– Strong wind conditions resulting in relatively stable generation	– Higher maintenance costs compared to onshore wind
– Less noise issues	– Regional wind correlation impacts profitability

Maturity	Potential ++	Cost €€€

1 IEA and Imperial College London, 2019

AFRY ÅF PÖYRY

Domestic and Nordic hydro power play a crucial role in flexibility but environmental norms and cross-border transmission capacity set limitations

THE FINNISH HYDRO CAPACITY IS ALMOST FULLY EXPLOITED

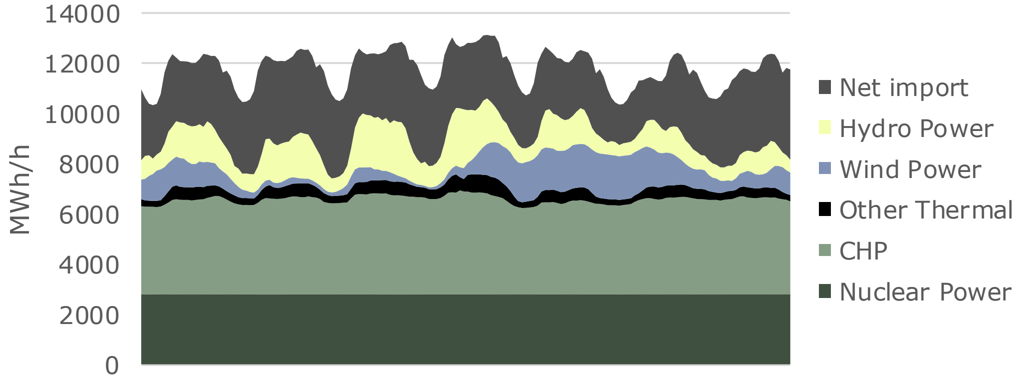
There are approximately 220 hydro power plants in Finland with a combined capacity of 3.2GW. In 2019, hydro generation in Finland was circa 12TWh representing 19% of the total generation.

Hydro power provides important flexibility to the Finnish power system. The output of larger hydro power plants can be adjusted in seconds or in minutes, and they provide storages over longer periods, enhancing security of supply.

Environmental regulations set limitations to flexibility by restricting water level variation which impacts hydro generators' ability to adjust output. There is also a significant share of non-flexible run-of-river hydro plants with no reservoirs. Potential for new hydro generation capacity is very limited as the remaining locations are protected.

Finland benefits from Swedish and Norwegian hydro power plants through strong interconnections and common power markets. Sweden and Norway have large hydro storage capacities, which enables seasonal storages and makes the Scandinavian hydro generation very flexible. Finnish cross-border transmission capacity however sets limits to how much can be imported (and exported) now and in the future. The interconnection capacity from Nordics to Central Europe is expected to more than double in the 2020s, which increases the demand for Nordic hydro flexibility.

HYDRO FLEXIBILITY BALANCES DEMAND AND WIND VARIATION[1]



BENEFITS	LIMITATIONS
– Flexible capacity across all time frames – Large energy storages	– Almost no potential to build new capacity due to environmental protection of unharnessed rivers – Precipitation dependent energy source – Environmental norms restrict potential for output adjustment

Maturity	Potential +	Cost €

1 Exemplary week from 2019, data from statistics of Finnish Energy Industry

Nuclear power production increases until 2030 and then decreases without lifetime extensions or new capacity

NUCLEAR GENERATION EXPECTED TO PEAK IN 2030

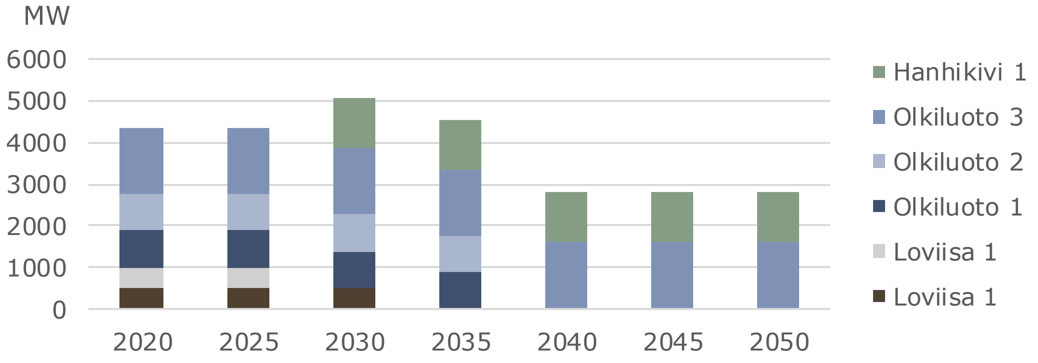
Nuclear power plays an essential role in the Finnish electricity production. The total capacity of the existing four reactors is 2.8GW. The reactors typically run at their nominal capacity and the output is generally not adjusted. In 2019, nuclear power production was 23TWh which corresponds to roughly a third of domestic electricity production.

Finland is one of the few countries in Europe in which new nuclear power capacity is constructed. Olkiluoto 3 will come online in 2020 adding 1.6GW of nuclear production capacity. Hanhikivi 1 has been announced to come online in 2028. Existing Loviisa 1 and 2 reactors are intended to shut down in 2027 and 2030 but their lifetime could be extended by 10 to 20 years. Extension applications have however not been submitted. Olkiluoto 1 and 2 are expected to close down in 2038 after 20-year extension granted in 2018.

In addition to Olkiluoto 3 and Hanhikivi 1, additional investments are not considered likely in the 2020s due to political uncertainties and current weak cost competitiveness against renewable generation.

Small modular reactors (SMRs), series-produced nuclear reactors ranging from ten to few hundreds of megawatts, are entering into clean energy technology option discussions. Serial production aims to drive down production and implementation costs, and cutting down delivery times. SMRs are already in licensing phase e.g. in USA, Canada and China. A task force set by the Finnish Ministry of Economic Affairs and Employment in 2019 examines opportunities to update the Nuclear Energy Act, which may pave the way for SMRs.

NUCLEAR CAPACITY DEVELOPMENT WITHOUT ADDITIONAL MEASURES



BENEFITS

- Stable electricity production
- Important low carbon technology
- Possible opportunity to extend the lifetime of the existing nuclear plants cost-efficiently

LIMITATIONS

- Existing nuclear is not suitable for balancing intermittent generation
- LCOE of new nuclear plants not competitive against many technologies including wind power
- Uncertainty over long-term electricity price level
- Vague political acceptability

Maturity	Potential ++	Cost €€

Bio-CHP improves security of supply but availability of biomass and uncertainty over electricity price risks investment appetite

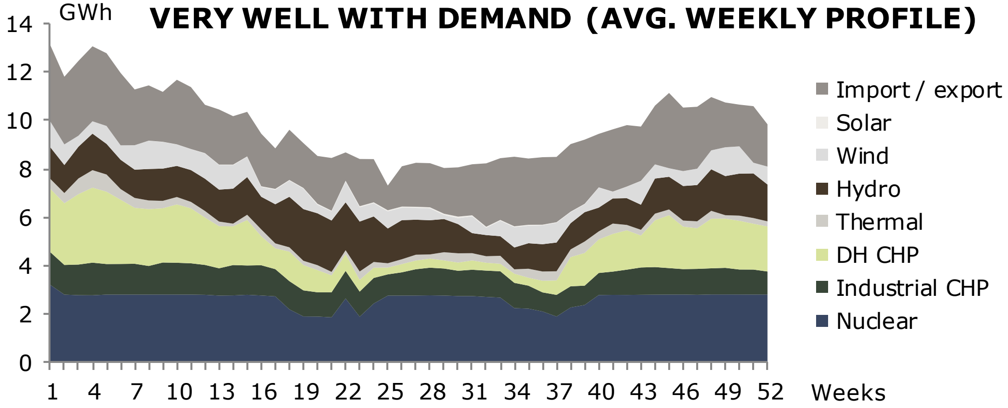
BIOMASS IS THE MAIN FUEL IN FINNISH CHP PLANTS

Bio-CHP refers to combined heat and power production plants that utilizes bio-based fuels like forest chips, biogas, biowaste, wood pellets and residues from forest industry. CHP generation covered 26% of the Finnish electricity demand in 2019. About 50% of wood-based electricity was generated by burning black liquor in 2017.

Some CHP plants have been replaced with heat-only boilers due to low electricity market price level. Decreasing CHP capacity impacts the security of supply because CHP plants produce electricity in winter when both heat and electricity demand are the highest due to low temperatures.

Many CHP plants have been converted to use biomass instead of fossil fuels due to tightened climate policy and coal ban in 2029. The availability of biomass can threaten further increase of bio-CHP, because biomass have multiple use cases. The future cost of biomass is hence one of the main uncertainties to bio-CHP in addition electricity price development. Biomass imports provide an alternative to domestic fuels especially in the coast and Eastern Finland.

DISTRICT HEATING CHP PRODUCTION CORRELATES VERY WELL WITH DEMAND (AVG. WEEKLY PROFILE)



BENEFITS	LIMITATIONS
– Mature and reliable technology	– Availability of biomass to CHP
– Dispatchable generation capacity	– Logistical limitations although sufficient drying and terminal capacity increases security of supply
– Biofuels serve as energy storage	– Sustainability criteria for biomass tightening
– High electricity supply in winter when the demand peaks	– Uncertainty over electricity price decreases investment appetite for CHP
– High share of domestic fuels	

Maturity	Potential ++	Cost €€

1 Weekly average production in 2019, Finnish Energy

Increase of solar PV power production is limited by lack of feasible seasonal storage technology

SOLAR PV HAS REACHED GRID PARITY IN MANY COUNTRIES

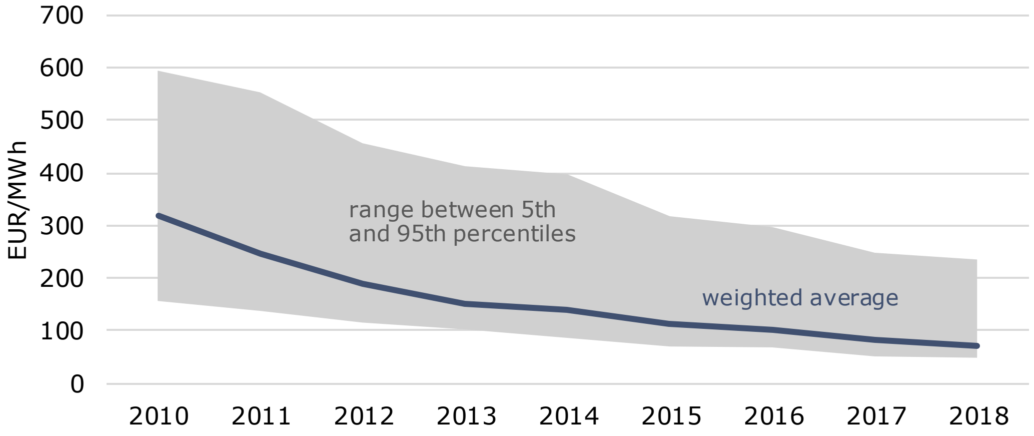
Photovoltaic (PV) technology has developed drastically over the past years. Development has lowered the manufacturing costs and increased capacity factors which can now be over 20%. As a result, the levelized cost of energy dropped by nearly 80% from 2010 to 2018[1].

Although majority of the European solar power investments have resulted as a consequence of various subsidy and tax schemes, large merchant projects are being realized already in as north as Denmark. PV is the most economic new investment among electricity sources in Southern Europe. Economies of scale drive down costs of utility-scale projects compared to smaller distributed installations.

Solar power is becoming attractive in Finland for commercial and residential customers when taking into account avoided grid tariffs and electricity taxes. At the end of 2018, the solar PV capacity in Finland was approximately 120MW implying an increase of 82% compared to 2017[2].

Annual solar radiation in Southern Finland is equivalent to the amount in Northern Germany. The radiation however varies seasonally due to Finland's northern location. As the availability of solar energy is highest in summer while the demand for energy peaks in winter, seasonal storages is required in order to accommodate greater shares of PV generation. Solar generation is also weather-dependent which creates a need for short-term flexibility.

GLOBAL SOLAR PV LCOE DEVELOPMENT[3]



BENEFITS

- Low barriers for entry for different types of producers (not only energy and industrial companies)
- Cost levels expected to decrease significantly
- Daily profile correlates with certain electricity demand profiles, e.g. HVAC

LIMITATIONS

- Very limited availability in winter
- Lack of seasonal storage
- Intermittency

Maturity	Potential +	Cost €€

1 ETIP PV, 2019
2 Energiavirasto, 2019
3 IRENA, 2019

Gas generators can be fueled by biogas and synthetic gas or natural gas combined with CCS but costs may limit the economic potential

GAS GENERATION CAN DELIVER SHORT AND LONG-TERM FLEXIBILITY

Gas utilization in power generation has declined in Finland for the past decade as a result of increased energy tax on natural gas, price development of competing fuels and increased carbon price. Finland opened its gas market for competition at the beginning of 2020 after commission of Balticconnector pipeline to Estonia. In Europe, natural gas has been replacing coal in power generation since higher carbon prices have made coal uncompetitive against gas.

Gas used in power generation today is mostly natural gas, but clean gases such as biogas or synthetic gas can be used as well. Limited availability of biogas and high cost of synthetic gases restrains the economic potential of the cleaner gases.

Installation of carbon-capture and storage (CCS) technology would capture up to 90% of CO_2 emissions from natural gas, or make clean gas combustion emissions negative, although the energy required in the process raises the cost of the power plant. As of today, CCS has not been fitted to gas-fired generation.

Gas-fueled power generation technologies differs in flexibility capabilities. Combined cycle gas turbines (CCGTs) are highly efficient power plants but often run according to heat needs in CHP plants. They however provide longer-term flexibility. Open cycle gas turbines are simpler design, which makes them cheaper but less efficient, but they can be ramped up fast and adjusted easily.

BENEFITS	LIMITATIONS
– Gas-combustion is mature technology	– Limited availability of biogas
– Flexible generation for multiple timescales	– High costs of synthetic gases
– CCS technology can be fitted in gas-fired power plants	– CCS technology is still under development

Maturity	Potential +	Cost €€(€)

AFRY
ÅF PÖYRY

Strong electricity transmission network and adequate interconnections are a prerequisite for utilization of clean and affordable electricity

NETWORK PROJECTS TAKE TIME AND MIGHT CAUSE CHALLENGES FOR NEW RES CONNECTIONS

Adequate electricity transmission and distribution network ensures that electricity can flow from generation to consumption without undue curtailments. The Finnish transmission and distribution networks are strong and Finland is relatively well-connected to its neighboring countries.

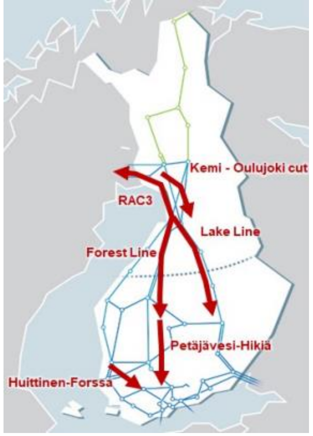
Finland relies currently heavily on electricity imports. In 2019, Finland imported 20TWh, representing 23% of demand. New AC interconnector toward Northern Sweden is coming online in 2025.

Fingrid, the Finnish transmission system operator, invests circa M€ 100 annually in the national transmission grid in order to accommodate increasing North-South power flow resulting mainly from the increasing wind power capacity in Northern and Western Finland. Majority of electricity consumption is located in Southern Finland.

Electricity consumption concentrates in larger cities due to urbanization and electrification of transport and heat. Rapid geographical consumption changes can be expected with a relatively short time period if heavy industry, including steel and chemical industry, will be electrified.

High-level overview of investments to transmission grid 2019-2030[1].

Replacement of Fennoskan 1 link to Sweden will reach end of its lifetime at late 2020's but options to extension are being seeked. Replacement will take place in 2030's.



Transmission capacity to Finland from	GW
Sweden	2.7
Norway	0.1
Estonia	1.0
Russia	1.5

BENEFITS	LIMITATIONS
– Mature technology	– Long construction lead times, especially for cross-border investments
– Enables economic generation dispatch across a wider geographical area	– Pressure to keep tariffs on a moderate level
– Strong network already	– Uncertainty with regards to location of new generation and demand
– Reasonable costs	

Maturity	Potential +++	Cost €€

1 Picture: Fingrid Oyj

LOW CARBON ENERGY TECHNOLOGIES

Flexibility in the electricity system

AFRY

ÅF PÖYRY

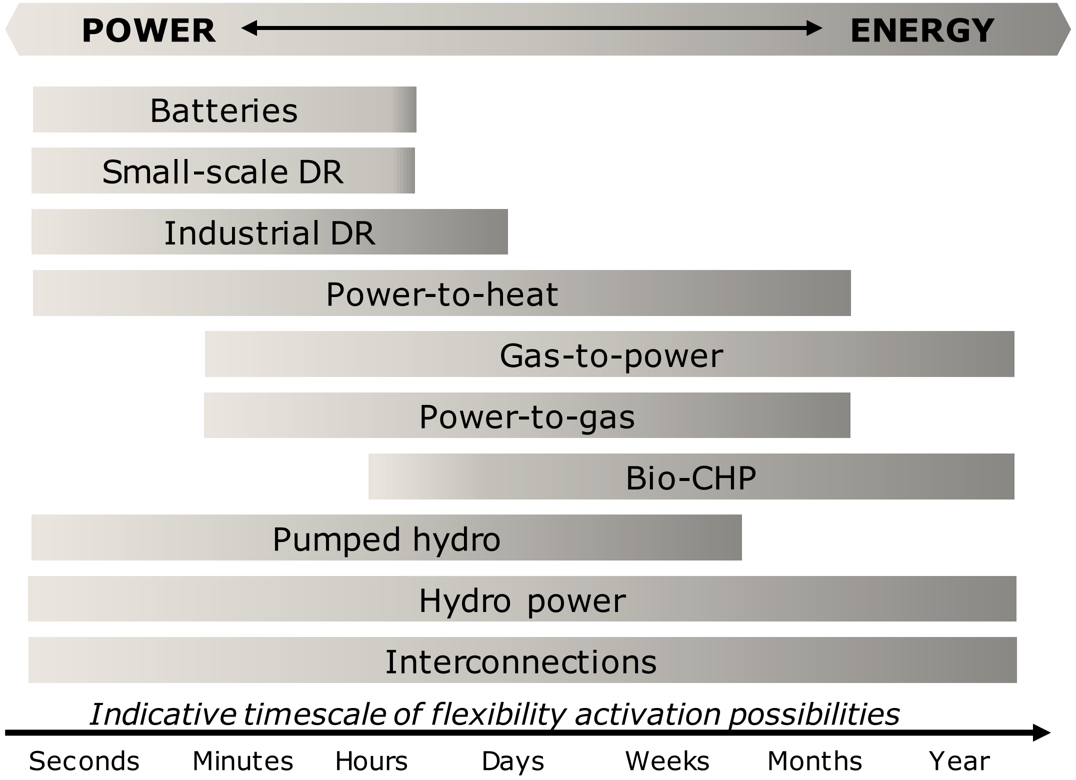
Electrification of industries, mobility and heating together with increased price volatility drive the flexibility investments

Technology	Investment cost or energy cost level today	Expected cost development	Techno-economic potential[1]	Remarks
Industrial demand response	500-2000 €/MWh	→	++	– Availability depends on the prevailing operational situation in industry – Electrification expected to increase the potential
Power-to-heat	190 - 610 €/kW	↘	++	– Heat pump optimization based on both electricity and heat prices – Change in taxation enhances economic attractiveness of electric boilers and industrial heat pumps
Gas turbine	c. 400 €/kW	→	+	– Limitations due to CO_2 emissions of natural gas, availability of biogas for energy production and cost level of synthetic gas
Power-to-gas	750-1200 €/kW	↘	+	– Gas infrastructure can accommodate only a certain share of hydrogen – Not yet economically feasible
Distributed demand response	10-500 €/kW	↘	+	– Provides short-term flexibility – Many boundary conditions for EV and electric heating optimization
Batteries, commercial and utility scale	1000-3000 €/kW	↘	++	– Allows short-term production optimisation and frequency management – Economies of scale reduce costs
Pumped hydro	c. 1000 €/kW	→	+	– Price volatility needs to increase for pumped hydro to become profitable

1 In Low carbon scenario which is described later in this report
Sources: AFRY (Pöyry and ÅF), other sources mentioned in the technology description later in the report

Distributed resources can support short-term balance management while long-term flexibility poses more challenges

FLEXIBILITY CAPABILITIES



- Short-term flexibility - from seconds to hours
  - Use cases in balancing demand and supply forecast errors, outage management and daily grid and energy fee optimization
  - Can be provided by various types of technologies, suitable especially for distributed resources
- Mid-term flexibility – regulation from hours to weeks
  - Need increases to balance intermittent renewable energy variation
  - Electrification of other sectors increase availability of mid-term flexibility. However domestic and Nordic hydro generation can represent the majority of daily regulation
- Long-term flexibility - from weeks to months
  - Required to cover peak energy demand in cold, dark and calm winter days when no wind and solar energy is available
  - Clean technologies that have the best capability to store large energy quantities in an efficient way are dispatchable generators like hydro power with storages and bio-fuel-fired CHP plants in Finland or in neighboring countries

Industrial demand response can provide additional flexibility to power system

CORE BUSINESS IS A PRIORITY

The Finnish industry consumed 39 TWh of electricity in 2019, representing 46% of total demand. Industrial equipment that can provide demand response are e.g. melting furnaces, industrial stoves, compressors, fans, pumps, electrical boilers and heat pumps. Each technology has different abilities to adjust electricity consumption in terms of reaction times and duration of the activation.

The availability of industrial demand response is dependent on at least production targets; process status and capacity; interim storage capacity and utilization; environmental and security restrictions; and workforce availability.

The Finnish industries have a long experience from participating in electricity wholesale and reserve markets. The potential of industrial demand response is estimated to be in the order of 1.0-1.5GW, depending on the situation. The price levels depend on the market and technology in question.

Electrification of industries offers potential for greater industrial demand response capacity. This is described in more detail later in this report.

INDUSTRIAL FLEXIBILITY POTENTIAL TODAY[1]

INDUSTRY	ESTIMATED TECHNICAL POTENTIAL	DURATION OF ACTIVATION
Chemical industry	75-150 MW	Hours
Metal industry	200-300 MW	Hours
Paper industry	500-600 MW	Hours
Data centers	10-200 MW	Minutes

+ BENEFITS

- Opportunity for increase in technical potential
- Typically smaller investments needs compared to generation or storage

– LIMITATIONS

- Availability depends on multiple non-electricity related factors

Maturity	Potential ++	Cost €€

1 Pöyry, Demand and supply of flexibility, 2018

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Demand response from electrified heating and transport sectors can deliver short term flexibility for electricity system

ELECTRIFICATION OF DISTRICT HEATING PRODUCTION CAN INCREASINGLY ABSORB EXCESS ELECTRICITY

Intensifying the interplay between electricity, heat and transport, a phenomenon called also as sector integration, can benefit the whole energy system and especially add flexibility in the electricity system. The integration is already present in forms of CHP optimization between shares of electricity and heat, and electric heating in both residential and large-scale electric boilers. However high taxation of electricity and electricity market prices has limited the extent in the past.

The government aims to cut the electricity tax of district heat producing heat pumps by changing the taxation class from 1 to 2 and reducing the tax level of class 2 to EU minimum. The announced changes reduce the taxes from 22.5€/MWh to 0.5€/MWh. This reduces economic barriers from interaction between electricity and heat, providing better opportunities for sector integration.

BENEFITS	LIMITATIONS
– Controllable heat pumps and electric boilers are mature technology – Large DH storages can absorb substantial quantities of energy – Electrification of heat reduces emissions from heat sector	– Need for large heat storages for mid-term storing

Maturity	Potential ++	Cost €
(full)		

RESIDENTIAL AND COMMERCIAL DEMAND RESPONSE COMES MAINLY FROM HEATING, COOLING AND EV CHARGING

Residential and agriculture sectors consumed 24TWh of electricity in 2019, representing 28% of total demand in Finland. Largest potential for demand response are currently in back-up power systems from commercial actors, electric space and water heating, and in electric vehicle charging in the future. The *maximum technical* load control potential of electric heating is estimated 1000-3000MW in winter and 600-1800MW in summer.[1]

The availability of distributed flexibility depends on time and customer preferences. The profitability of residential and commercial demand response derives mostly from more efficient use of energy due to high electricity taxation and optimizing distribution tariff which together form most of the electricity bill.

BENEFITS	LIMITATIONS
– Small-scale heat control equipment is maturing technology – Empowering and encaging customers – Smart services can contribute to energy efficiency	– Only intra-day flexibility – Large pool of devices required to make an impact

Maturity	Potential ++	Cost €€
(three quarters)		

1 DR pooli (2015). Kysynnän jousto – Suomeen soveltuvat käytännön ratkaisut ja vaikutukset verkkoyhtiöille

Electric batteries can serve both system-wide and local needs in short time periods

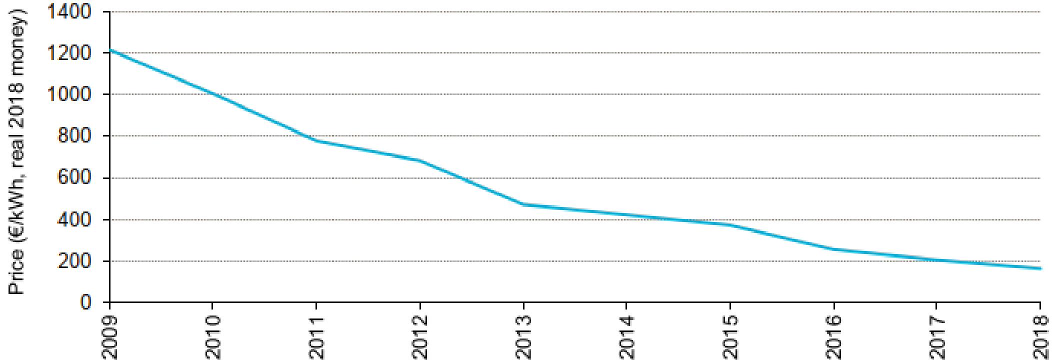
MOST BATTERIES ARE EMBEDDED IN ELECTRIC VEHICLES

Battery storage technologies have improved rapidly during the past years. The costs of Li-ion batteries decreased by over 80% between 2010 and 2018 thanks to technology development for automotive industry. In 2018, volume weighted average costs for Li-ion batteries were 176 USD/kWh[1]. There is still considerable potential for cost reduction and performance improvement, and in 2018 it was expected that Li-ion battery costs could drop by nearly 30% during the next five years.

Although Li-ion batteries dominate the battery market, costs of other technologies with different technical capabilities are expected to fall as well. Capacities of electric batteries range from few kilowatts to tens of megawatts and energy-to-power ratios from less than 1 to higher than 10, depending on the technology and application.

Battery storages offer diverse capabilities and they can be used for multiple purposes, especially in ancillary services for electricity system management or in consumption or generation optimization on a smaller scale.

HISTORICAL PRICE EVOLUTION IN AUTOMOTIVE LI-ION BATTEY PACKS[2]



BENEFITS	LIMITATIONS
– Versatile technical capabilities – Rapidly improving technology – Electrification of transportation drives investments despite low electricity price volatility	– Not suitable for mid- and long-term energy storage – Overall storage capacity remains limited on a system scale – Expensive compared to flexible generation technologies

Maturity	Potential +	Cost €€€

1 Bloomberg New Energy Finance, 2019
2 TSI, METI, HIS, Citi Research, Bloomberg New Energy Finance and Pöyry Management Consulting

Power-to-gas (P2G) and pumped hydro storages can provide both supply and demand side flexibility

P2G TECHNOLOGY REQUIRES R&D TO SCALE UP AND INVESTMENTS IN HYDROGEN INFRASTRUCTURE

Power-to-gas refers to technologies in which electricity is used to produce fuels like hydrogen through electrolysis, or further convert hydrogen into methane by methanation. Electrolysers have good regulation capabilities while methanation is less flexible. The gaseous fuel may be used in e.g. in industrial processes and in heavy-duty transport. The fuel can also be utilized to generate electricity later on in gas motors or turbines.

The P2G technology is still at development phase but scaling up rapidly. Electrolysis facilities range from <1MW to 100 MW. For P2G to become competitive, progress is required especially in large-scale electrolysis facilities to drive down unit costs. Hydrogen Europe targets H_2 cost decrease from EUR 10-15/kg currently to EUR 3/kg in their 2030 roadmap, resulting in roughly EUR 100-200/MWh cost for power production.[2]

+ BENEFITS	– LIMITATIONS
– Supply and demand side flexibility	– Poor efficiency
– P2G fast developing technology	– High costs
– P2G applicable where electricity network cannot be upgraded	– Hydrogen is challenging to store
– Methane suits for long-term storing	– Distribution infrastructure improvements and investments are needed if wider application

Maturity ○	Potential +	Cost €€€

POTENTIAL FOR HYDRO STORAGE CAPACITY IN FINLAND IS LIMITED

The opportunities to develop pumped hydro storage in Finland are limited – the only identified potential location is old Pyhäsalmi mine. The full-scale power plant could have a maximum peak power of 75 MW, energy capacity of 530MWh and efficiency of approximately 77%. Technical planning for a power plant has been started. Pumped Hydro Storage Sweden, the developer of the demo plant, announced in 2019 that it will apply for 30MEUR investment subsidy for renewable generation from the state.[1] The project is not currently profitable.

+ BENEFITS	– LIMITATIONS
– Mature technology	– Weak profitability due to low price volatility
– Provides short-term flexibility	– Little technical potential in Finland
– Limited impact to environment	

Maturity ●	Potential +	Cost €€

1 Lianapress 27.2.2018, Talouselämä 7.12.2019. 2 Hydrogen Europe. Technology Roadmaps. September 2018.

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LOW CARBON ENERGY TECHNOLOGIES

Heat production and flexibility

SUMMARY OF HEAT PRODUCTION TECHNOLOGIES

Heat pumps help capturing heat from multiple sources

Technology	LCOH[1] in Finland today	Expected cost development	Techno-economic potential	Remarks
Bio-CHP and heat-only boilers	35-50 €/MWh	→	++	– Availability and sustainability of bio fuels – Uncertainty of future electricity price limits investment appetite in CHP – Increasing demand expected to increase biomass prices
Industrial waste heat	25-30 €/MWh	→	+	– Infrastucture extension to recover heat across longer distances – Uncertainty of long term availability locally, dependency on industrial activity level
Heat pumps for ambient heat	35-100 €/MWh	↘	+++	– Economies of scale decrease the cost – Increases electricity consumption in locations close to population centers
Geothermal (deep heat)	30-120 €/MWh	↘	+(++)	– Full techno-economic potential for deep heat not known yet
Solar thermal	40-130 €/MWh	↘	-	– Strong seasonality that contradicts heat demand limits utilization of technology in Finland
Nuclear SMR heat	?	↘	?	– Political and social acceptance of nuclear reactor in proximity to population centers challenging – No commercial installations yet
District heat storages	1300-5000 €/MWh (capacity)	→	++	– Existing caves can serve for weekly storage for hot water – Offers seasonal storage capacity
Heat demand response	-	↘	+	– Avoidance of peak generation capacity within a day – Dynamic pricing to incentivize customers to opt new services

1 Levelized cost of heat
Sources: AFRY (Pöyry and ÅF), other sources mentioned in the technology description later in the report

Biomass-fired heat-only boilers can replace bio-CHP in heat production if expectations of long-term electricity price development remain weak

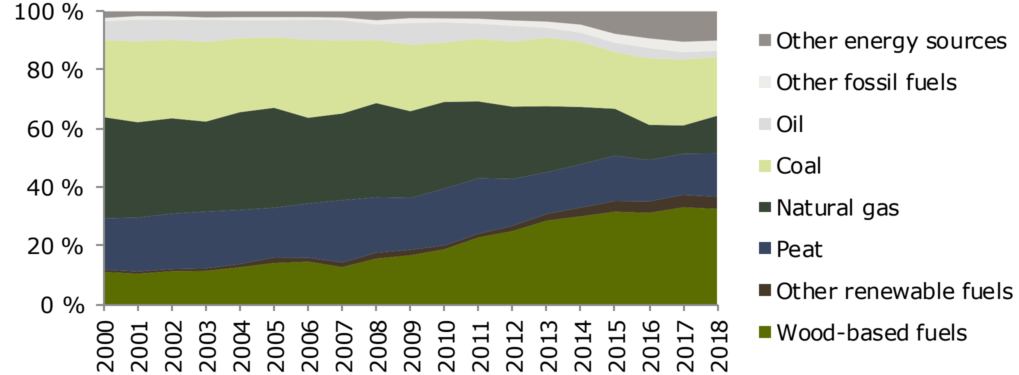
More than a third of district heat production in Finland is based on renewable fuel sources and the use of renewables has been growing rapidly in the 21st century (top-right chart). Biomass has been the main fuel in heat production conversions when reducing the share of fossil fuels.

Currently a biomass-fired heat-only boiler (HOB) is typically the least cost option for new district heating baseload capacity in terms of levelised cost of energy (LCOE). For a CHP investment to be profitable, the additional revenue from electricity market should exceed the increased costs compared to a HOB dimensioned according to same heat demand (bottom-right chart). Full load hours c. 5000 MWh/MW correspond roughly to a base load unit in a DH network and c. 7000 MWh/MW to an industrial CHP.

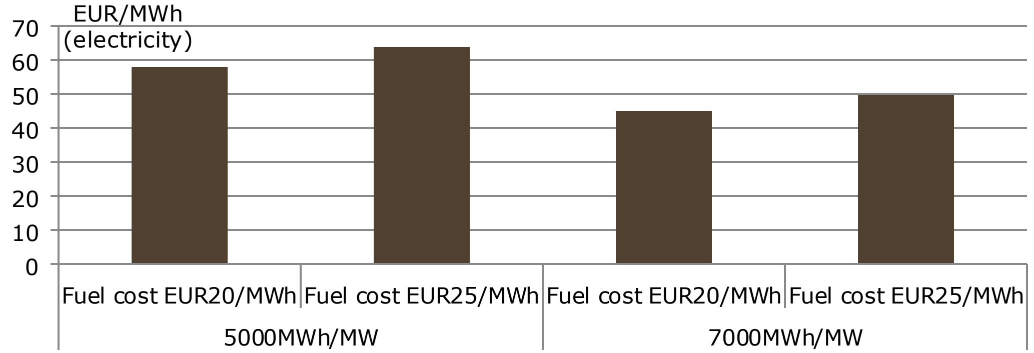
BENEFITS	LIMITATIONS
– Mature and reliable technology	– Availability and price development of biomass
– High share of domestic fuels	– Sustainability criteria for biomass tightening
– Biofuels serve as energy storage	– Uncertainty over electricity price decreases investment appetite for CHP
– High electricity supply in winter when the demand peaks in case of CHP	

Maturity	Potential ++	Cost €€

ENERGY INPUT DEVELOPMENT FOR DISTRICT HEATING[1]



BREAK-EVEN ELECTRICITY PRICE FOR CHP AGAINST HOB IN TWO CASES FOR FULL LOAD HOURS (DH AND INDUSTRIAL)



1 Source: Finnish Energy

Heat pumps are expected to play a clearly larger role in the future also in district heat production

INFRA EXPANSIONS AND LARGE HEAT PUMPS ARE NEEDED TO RECOVER WASTE HEAT

Heat pumps extract heat from air, water and ground and they can be utilized to recover waste heat from industrial processes. The majority of the 0.9 million heat pumps in Finland are rather small in size and they are installed in residential houses. The sizes of heat pump systems are increasing and megawatt-size heat pumps are becoming more common in commercial buildings and in district heating production.

Heat pumps produced 7TWh of heat in 2018. Heat production with heat pumps is expected to increase also in the district heat network. The announced reduction of electricity taxation from 22.5€/MWh to 0.5€/MWh increases the competitiveness of large-scale heat pumps.

Heat pumps can provide short-term flexibility during periods of high electricity prices; in DH systems even for a longer period given that there is enough other capacity available.

+ BENEFITS	– LIMITATIONS
– Heat pumps is a mature technology – High technical potential – Diversification of heat supply – Additional revenue stream for industry	– Availability of heat varies between the installations – Need to expand district heat infrastructure

Maturity ●	Potential ++	Cost €€

Many industrial facilities produce great amounts of heat for processes, or as a by-product, like in data centres. Motiva has estimated that the technical potential for industrial excess heat was 16TWh in 2017 but the long distances between the industrial site and heat network limit opportunities economic potential to a fraction of the overall potential. However tightening climate policies have created an urgency to explore the more challenging origins. One example is transmitting of Neste and Borealis' excess heat 40km from Kilpilahti to Helsinki Metropolitan area, which would over a third of the heat demand in Helsinki area.

ELECTRIC BOILERS IN DH PRODUCTION

Electric boilers in district heating production is a mature technology but it has not been widely utilised since high electricity taxes, electricity prices and network charges make them less profitable compared to biomass-based heat production. Electric boilers are very flexible and they could easily benefit the periods of low electricity prices.

+ BENEFITS	– LIMITATIONS
– Electric boilers are a mature technology – High efficiency – Possibility to optimize heat production according to electricity prices	– Increase electricity consumption during peak times

Maturity ◕	Potential ++	Cost €€

Geothermal heat has still uncertainties but if proven feasible it can capture a high share of district heating in certain networks

GEOTHERMAL HEAT HAS STILL UNCERTAINTIES OF THE TECHNOLOGICAL POTENTIAL AND BORING COSTS

Geothermal heat production may provide baseload heat into district heating network in the future. Medium-depth geothermal wells reach to depth of 1-4km and heat water to 15-40°C. Deep geothermal wells range from 6-8km of depth and produces 90-120°C hot water.

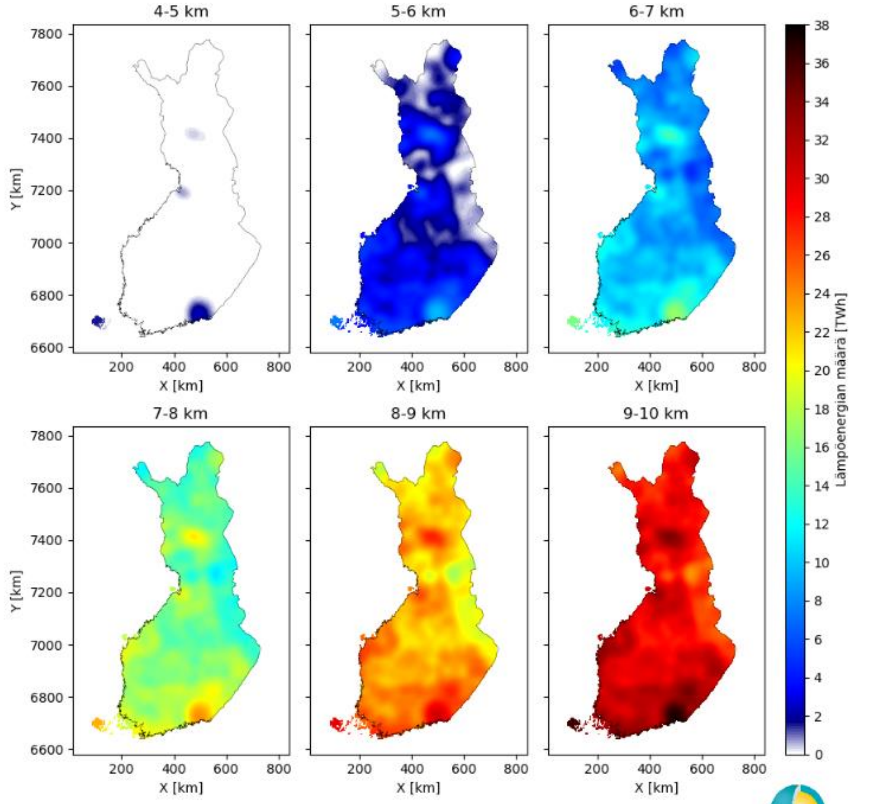
Estimates of LCOE for a medium-depth geothermal system range between 70 to 120 €/MWh and for a deep system between 30 to 50 €/MWh. Drilling accounts for the majority of the costs and if technique continues developing, geothermal heat becomes competitive with other heat production technologies.

The overall potential and technology cost forecasts remain uncertain. ST1 is conducting a pilot project of two 6.5-km-deep geothermal heating plant based on two wells in Espoo[1]. The 30-40MW system delivers heat throughout the year, which translates into 1.5GWh/a. Other projects has been planned in Finland.

BENEFITS	LIMITATIONS
– High efficiency	– Still in development phase
– Constant output	– Uncertainty over total potential and cost
– Possibility for seasonal heat storage	

Maturity	Potential +/++	Cost €€

THE POTENTIAL OF DEEP GEOTHERMAL HEAT IN FINLAND[2]



1 ST1, 2019
2 Geological Survey in Finland, 2019

Role of solar thermal and nuclear SMR district heat are uncertain due to seasonality and societal acceptance respectively

SOLAR THERMAL

Solar thermal heat can be produced in centralized facilities directly to district heating network, or in decentralized installations. An estimated LCOE for a large, 10 000 m² system with 4200MWh/a production is 50 €/MWh. However LCOE always depends on each system and the system cost should always be reviewed as a whole. Due to seasonality of solar radiation, a solar thermal system would decrease capacity factors of other heat production units in the same system unless seasonal storage is available. For smaller systems like residential and commercial buildings the investment cost without taxes varies between 400-1000 €/m² and the LCOE could reach over 100 €/MWh.

BENEFITS	LIMITATIONS
– Mature technology	– Strong seasonality that contradicts heat demand – Lack of seasonal storages

Maturity	Potential +	Cost €€

NUCLEAR HEAT

Small modular reactors, SMRs, could produce district heat with nuclear energy in future. SMRs that are designed to produce only low-temperature heat are simpler and hence enable reasonable costs. The levelised costs of heat (LCOH) of SMRs has been estimated to be able to reach 15 to 30 €/MWh[1] but the commercial development is still uncertain. VTT has announced that it starts designing a concept plan that is fit for Finnish district heating networks.

A major barrier for SMRs to become an option for heat production is currently the licensing process, which is designed for large units. District heat producing nuclear reactor would be placed closer to population centres, and it is not yet known what the public acceptance will be despite the high safety features.

BENEFITS	LIMITATIONS
– Stable heat production – Can generate very high temperature heat or steam	– Technology is in early development stage – Political uncertainty – Social acceptance in close proximity to population required in DH

Maturity	Potential +	Cost €

1 Think Atom. Nuclear District Heating in Finland, 2019

Large heat storages in district heating network can harness renewable energy up to seasonal scale while demand response flexes on diurnal basis

LARGER HEAT STORAGES FOR LONGER FLEXIBILITY

Most existing larger-scale heat storages are tanks for 90°C water owned by district heating companies. The capacities of the storages are dimensioned to enable optimizing daily district heat production and to enhance security of heat supply in local district heat networks. The capacities in Finland range typically from a few hundred MWhs to over 1GWh.

Storing heat has become more topical with increasing share of variable energy production. For example old oil storages can be converted into heat storages. Helen, a utility in Helsinki, launches a 260,000m^3 / 11.6GWh heat storage in Mustikkamaa in 2021. Heat suffices for four days with full discharge power of 120MW. The investment cost is roughly 15M€.[1]

The first seasonal heat storage in Finland is planned in Kruunuvuorenranta, Helsinki, with a capacity of 4.5GWh. It stores 18°C warm sea water in summer to be used later through heat pumps. Seasonal storing of heat in water or other medium would foster utilization of solar energy captured during summer.

HEAT DEMAND RESPONSE FOR PEAK LOAD SHAVING

Heat demand response from residential and commercial customers can enable overall peak demand reduction and hence enable avoiding start-up of peak load generation units. Demand response require investments which then also enable offering new services to the customers. Another benefit of the new services is higher energy efficiency if room temperature can be automatically lowered when dwellings are not occupied.

LARGE SCALE HEAT STORAGES

+ BENEFITS	− LIMITATIONS
– Mature technology – Cost efficient form of storing large amounts of energy – Suitability for seasonal storing	– Requires large spaces close to DH network, often in densely populated area

Maturity (full)	Potential ++	Cost €€

HEAT DEMAND RESPONSE

+ BENEFITS	− LIMITATIONS
– Means to avoid running peak production units – Opportunity for increased customer engagement	– Only intra-day flexibility – High number of customers needed to have an impact

Maturity (half)	Potential +	Cost €€

1 Helen, 2019

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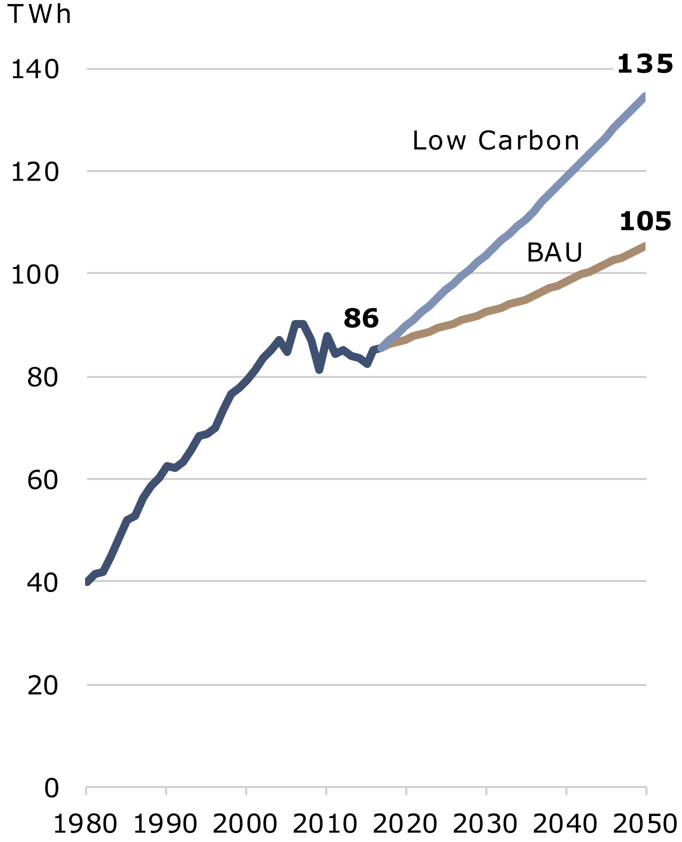
Demand and supply scenarios

DEMAND AND SUPPLY SCENARIOS

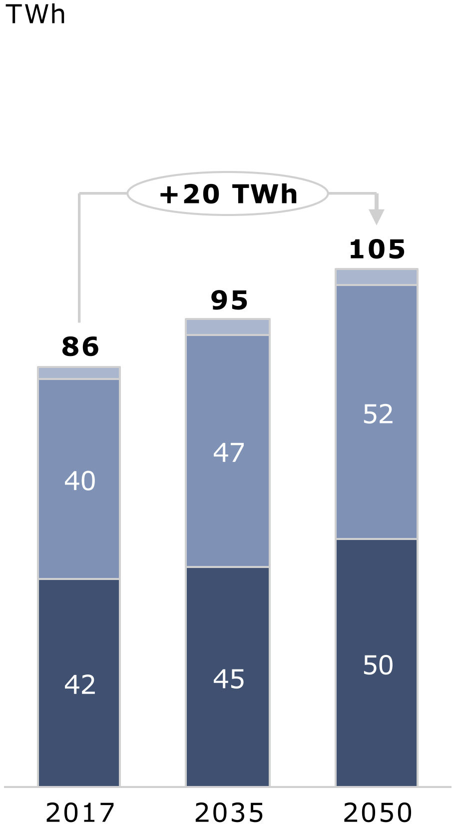
Demand scenarios

Industry Low carbon pathway is likely to increase electricity demand in Finland significantly compared to business-as-usual trajectory

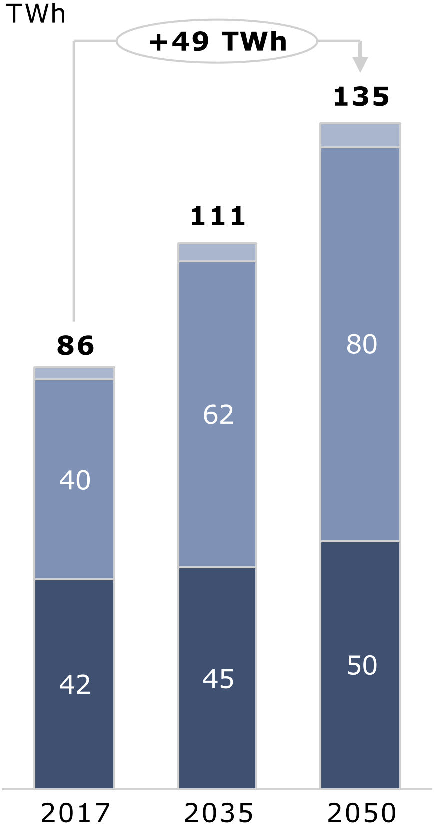
POSSIBLE DEVELOPMENT TRAJECTORIES FOR ELECTRICITY DEMAND IN FINLAND



BAU SCENARIO



LOW CARBON SCENARIO



Grid losses
Industry
Non-industry

SCENARIO ASSUMPTIONS

Electricity demand scenarios are based on industry Low carbon roadmaps and review of public demand projections

- **Industry demand** is mostly based on inputs from parallel ongoing sector-specific Low carbon roadmaps
- **Non-industry demand** is based on AFRY's high level review of selected recent energy scenario studies and is kept constant in both scenarios
- **Grid losses** are assumed to remain at some 3% of consumption

AFRY analysis

AFRY
ÅF PÖYRY

Reviewed demand forecasts project growth, but there is notable deviation between scenarios due to uncertainty in the development of key drivers

RANGE OF SELECTED DEMAND PROJECTIONS[1] (TWH)

Sector	2017	2035	2050
Industry	40	45-57	49-70
Services and public sector	19	21-25	24-27
Households	23	19-23	18-22
Transport	1	2-4	4-10
Transmission and distribution losses	3	3	3-4
Total	**86**	**92-106**	**100-127**

- Electricity demand (TWh) is projected to increase in all reviewed scenarios compared to current demand of 86 TWh in 2017
  - VTT: 96-106 and 105-127 TWh in 2035 and 2050
  - SKM: 92 and 100 TWh in 2035 and 2050
- The main drivers are also the main causes for uncertainty
  - Degree of electrification of industry
  - Development of data center capacity
  - Electrification of transportation
  - Electrification of household heating

DEMAND ASSUMPTION USED IN BAU-SCENARIO (TWH)

Sector	2017	2035	2050
Industry	40	47	52
Services and public sector	19	20	21
Households	23	21	19
Transport	1	4	10
Transmission and distribution losses	3	3	3
Total	**86**	**95**	**105**

- Electricity demand in BAU-scenario has been compiled by combining industry demand projections from Finnish Forest Industries, Technology Finland and The Chemical Industry Federation of Finland with AFRY's high level estimate of one possible scenario for non-industry demand
- Industry demand scenarios are presented in p.36
- For the purposes of this study, a growth trajectory resulting in the higher range of reviewed scenarios is assumed for non-industry demand
- Assumptions behind non-industry demand are summarised in p.35

1 AFRY analysis based on Hiilineutraali Suomi 2035 (VTT, 2020), Sähköntuotannon skenaariolaskelmat vuoteen 2050 (SKM, 2019)

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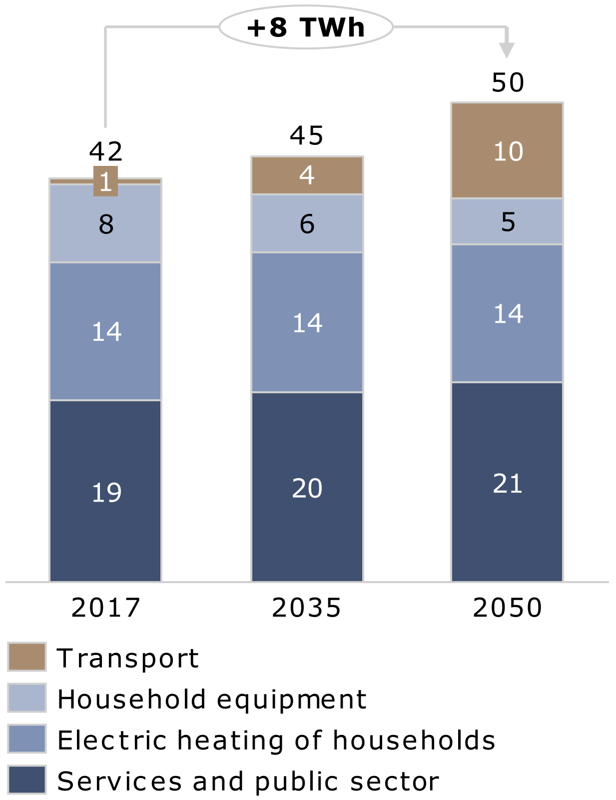
Electrification of transport is seen as the main driver for increased consumption in the non-industry sectors

ELECTRICITY CONSUMPTION OF NON-INDUSTRY SECTORS 2017-2050
TWh



Transport

- Includes electricity demand of railways (0.6 TWh in 2017) and road transport (0.2 TWh in 2017)
- There is uncertainty in the technical and commercial development of EV's as well as its market environment, which together impact market share growth of EV's in Finland's vehicle fleet (2.7 Million passenger vehicles in 2017)
- The scenario for transport electricity consumption is based on the targets referenced in the Action program for carbon-free transport published by the Ministry of Transport and Communications. The study estimates that transport sector would consume electricity some 3TWh in 2030 and 10TWh in 2045. The referenced scenario assumes some 2 M EV's by 2045 as well as electrification in other transport consumption segments such as heavy transport

Households

- Heat pumps continue gaining market share especially in the detached and row house segments and are expected to replace majority of current oil and other fossil fuel heating together with small shares of direct electric heating and district heating
- Net impact to electricity demand is estimated somewhat small, as demand growth from heat pumps is offset by the improved efficiency compared to direct electric heating. In addition, energy efficiency and climate change have negative impact on heating demand
- Electricity consumption of household equipment is assumed to decline 0.1 TWh p.a. as energy efficiency of equipment improves gradually

Services and public sector

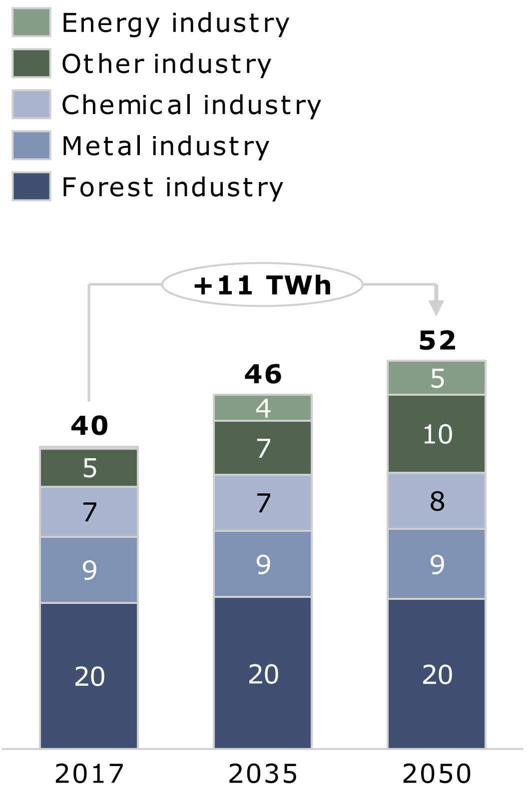
- Service sector's share of GDP has been increasing in the past and this trend is expected to continue resulting in minor growth in electricity demand
- Energy efficiency improvements and decline in public sector consumption partially offset this growth

A FRY analysis based on Statistics Finland, Hiilineutraali Suomi 2035 (VTT, 2020) and Action programme for carbon-free transport 2045 (Ministry of Transport and Communications, 2018)

Electrification of metal and chemical industries coupled with growth in data center and heat pump capacities may increase industry demand 40TWh

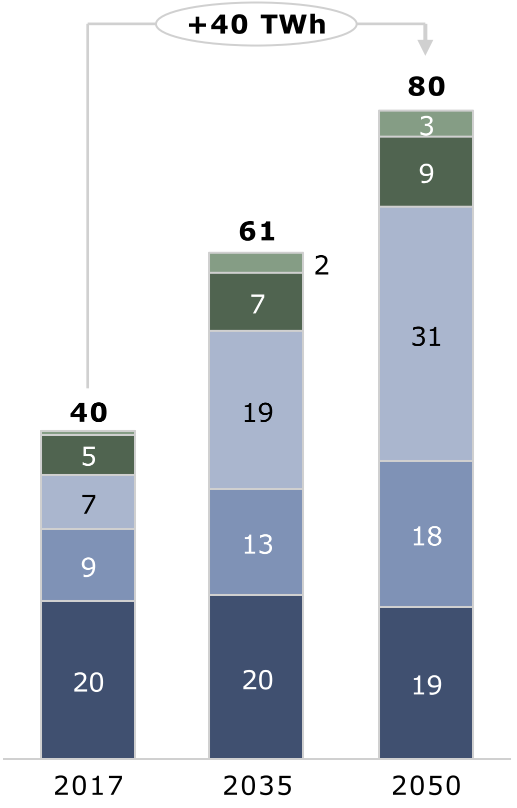
BUSINESS-AS-USUAL SCENARIO

TWh



LOW CARBON SCENARIO

TWh



A FRY analysis based on Statistics Finland (2018) and data received from Low carbon roadmap studies carried out for Finnish Forest Industries, Technology Finland and The Chemical Industry Federation of Finland

Energy industry

- Constitutes of heat pump electricity consumption (0.3TWh in 2017)
- Geothermal heat and more extensive utilisation of waste heat sources are assumed, resulting to increase of 5TWh in BAU scenario and 3TWh in Low-Carbon scenario electricity consumption by 2050

Chemical industry

- Increased production volumes lead to minor electricity demand growth in BAU-scenario
- Low carbon scenario assumes major investments in electrification of heating processes (+14TWh) and power-to-X technologies (+10TWh) increasing electricity demand by 24TWh by 2050, with demand starting to increase significantly after 2025

Mining and metal industry

- Minor growth in BAU-scenario from increased production volumes
- Electrification of steelmaking is estimated to increase demand by some 9TWh (hydrogen production +7TWh, process electrification +2TWh)

Forest industry

- Improvements in productivity and energy efficiency measures are assumed to offset most of increased electricity consumption. Demand is driven by production volume growth and a degree of electrification, resulting in almost stable demand in 2015-2050

Other industry

- The main sectors represented in the category are manufacturing industries and ICT-sector
- Electricity consumption of data centers is estimated at more than 1TWh in 2017 and assumed to grow by 3-4TWh by 2050

Summary of electricity demand assumptions in industry sector

Industry	Business-as-usual scenario	Low carbon scenario
Forest	– No change in electricity consumption due to Forest industries seeing positive development in productivity and energy efficiency measures which offset the increased electricity consumption from production volume growth	– Further energy efficiency measures result in slightly lower electricity demand, despite minor electrification measures
Mining and Metal	– Minor growth in BAU-scenario from increased production volumes	– Electrification of steelmaking process is estimated to increase demand by some 9TWh by 2050 – Majority of additional electricity demand from hydrogen production as a reduction-agent in steelmaking. Also electrification of other metallurgical processes and internal transport in mines.
Chemical	– Energy efficiency improvements largely offset increased consumption from volume growth	– Electrification of process heating with technologies such as hybrid boilers, heat pumps, coils and electric furnaces – Low-temperature heat demand (below 200°C) is assumed to be electrified first, highest temperature applications e.g. electric furnaces (up to 1000°C) assumed available only in 2040s – Power-to-H_2 electricity demand leaps in 2030s (5TWh in 2035)
Energy	– Constitutes of heat pump electricity consumption (0.3TWh in 2017) – Geothermal heat and more extensive utilisation of waste heat sources are assumed, resulting in 5TWh increase in electricity consumption by 2050	– Geothermal and waste heat sources are assumed to be used more but somewhat limitedly due to already high industrial demand causing higher prices and thus decreasing competitiveness against CHPs, resulting in 3TWh increase in electricity consumption by 2050
Other	– Electricity consumption of data centers grows from more than 1TWh in 2017 by 4 TWh in 2050 – Estimated by assuming 90% operating factor for the three largest datacenters (Google, Telia, Yandex) 140MW and 5%p.a growth of demand. (This does not consider the hundreds of smaller datacenters already in operation).	– Electricity consumption of data centers grows from 2017 by 3 TWh in 2050 as technology disruptions lead to better energy efficiency, thus resulting in lower data center consumption compared to BAU-scenario – Growth in ICT does not yet factor in impact of 5G and Edge-technologies – Electrification also in other manufacturing sector, but quantities relatively small

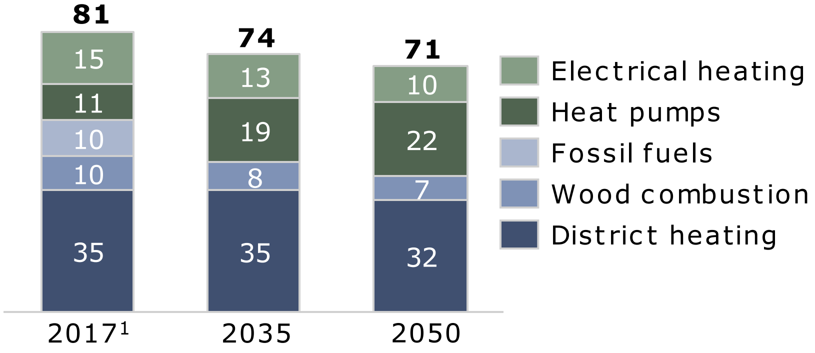
District heating is estimated to roughly maintain its current market position

SCENARIO ASSUMPTIONS

- Market size i.e. heat demand is a result of building stock volume and specific heat consumption. The main drivers for heat demand are new construction, renovation activity, demolitions, building codes as well as climate change
- Market shares of heating solutions is in part determined by relative cost position of heating solutions and partly by technical restrictions as well as consumer preferences
- At current building rate, some 100 GWh detached and row buildings and 100 GWh apartment buildings are constructed annually[2]. District heating is likely to capture majority share of apartment buildings but heat pumps are seen to continue gaining market share in detached and row buildings. Specific heat demand for new buildings is expected to decline as requirements for energy efficiency are increasing
- Overall heat demand is expected to decline some -0.5% p.a. as a result of energy efficiency improvements in building stock and average temperatures increasing from climate change impact
- District heating demand is considered continue increasing marginally until 2030 and decline at -0.5% p.a. in years 2030-2050. The assumption until 2030 is based on recent study by Pöyry[3]
- Fuel oil represents some 9TWh of heat production in 2017. Finland has set a target of phasing out fuel oil in heating by the beginning of 2030s[4]. Majority of oil heating is assumed to be replaced with heat pumps and some with district heating and electric heating by 2035
- Heat pumps are also likely to replace some portion of current electrical heating due to energy efficiency benefits

HEAT END-USE IN BUILDINGS*

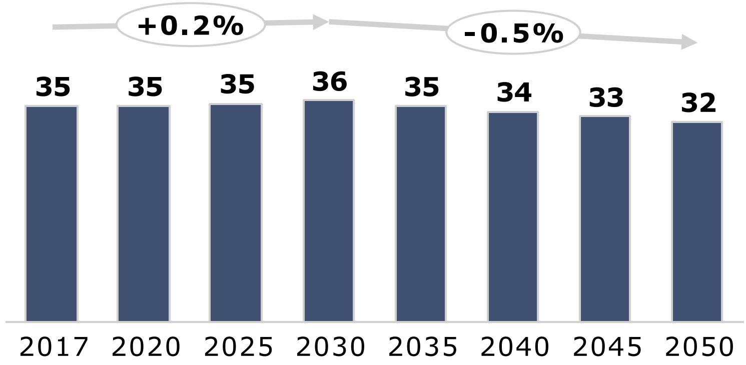
TWh



*Used in both BAU and Low carbon scenarios

SCENARIO FOR DISTRICT HEAT DEMAND

TWh



1 Statistics Finland (2018) | 2 Hajautetun uusiutuvan energiantuotannon potentiaali, kannattavuus ja tulevaisuuden näkymät Suomessa (Pöyry, 2017) | 3 Huoltovarmuus Energiamurroksessa (Pöyry, 2019) | 4 Finland's Integrated Energy and Climate Plan (Ministry of Economic Affairs and Employment, 2019)

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DEMAND AND SUPPLY SCENARIOS

Supply scenarios

Finnish energy sector faces major changes in the upcoming years to meet carbon neutrality targets and in improving self sufficiency of power supply

Supply scenarios developed in this study are based on investments made for two primary reasons:

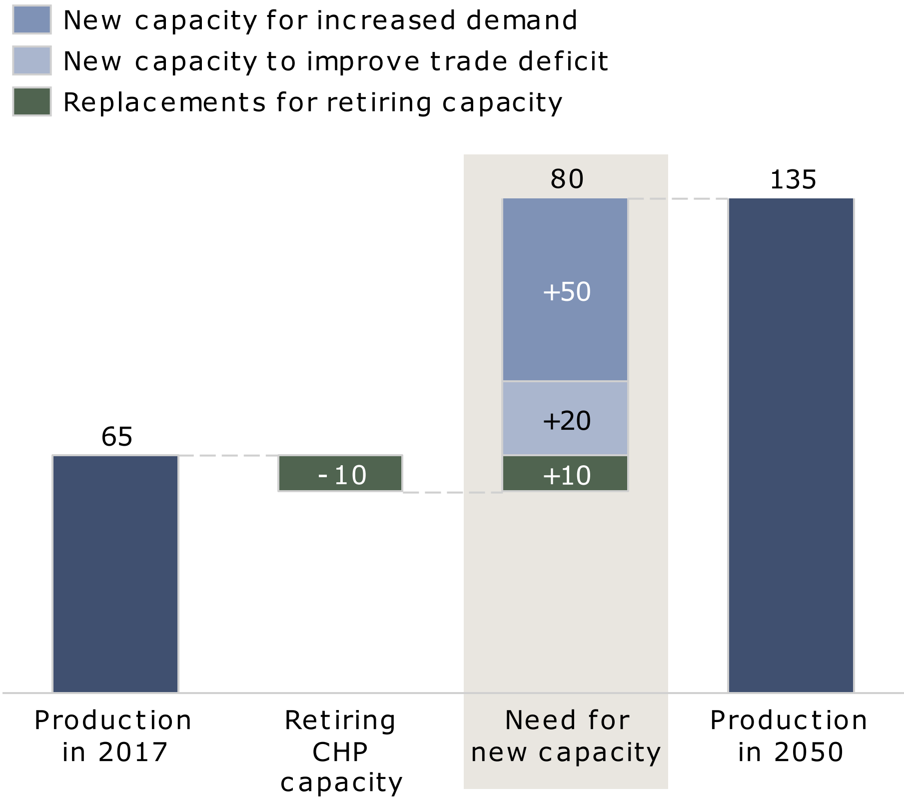
1. Replacements of retiring capacity and fuel mix conversions
   - Based on technical age of assets, AFRY estimates that some 10TWh of existing cogeneration power production will retire by 2050
   - Currently about 20% of electricity generation and 50% of district heating is produced with fossil fuels which will be needed to be phased-out to meet carbon neutrality targets
2. New capacity build-up to meet increased demand
   - Electricity demand increases by some 20-50 TWh in BAU and Low carbon scenarios by 2050
   - Finland is currently a net importer of electricity with annual imports of 20TWh
   - In total this amounts to a need of 40-70 TWh of new electricity generation capacity by 2050 if Finland targets carbon neutrality and energy self-sufficiency

Technology and fuel choices for these investments are subject to:

- Cost development of production technologies (LCOE)
- Market outlook and expectations of electricity and fuel prices
- Feasible commercial and technical potential

AFRY has assessed supply options based on the above considerations and compiled possible supply mixes that cover the demand scenarios.

ILLUSTRATION OF INVESTMENT NEEDS FOR NEW POWER CAPACITY IN LOW CARBON SCENARIO
TWh



Cogeneration decreases by 10 TWh while renewable electricity production increases some 40 TWh by 2050 in BAU-scenario

Increase of domestic generation reduces net imports

- Increase of domestic power generation is important given that Nordic electricity consumption is expected to increase by about 40 TWh by 2030 and further by about 65 TWh by 2050 (SKM)
- In BAU scenario, domestic production increases from 65TWh in 2017 to 91TWh in 2035 as a result of wind power investments and new nuclear plants being online in 2035
- Net imports of electricity from the Nordic countries fall to 4TWh in 2035, after which they will increase to 14TWh by 2050 due to a decline in nuclear power generation and increasing demand

Decline in cogeneration

- Cogeneration is expected to fall from its current level of 21TWh electricity to 15TWh in 2035 and to 11TWh in 2050
- Decline in production volumes is a result of declining capacities, as existing CHP fleet is replaced only partly by new CHPs due to moderate electricity prices and more competitive alternatives for power generation being available

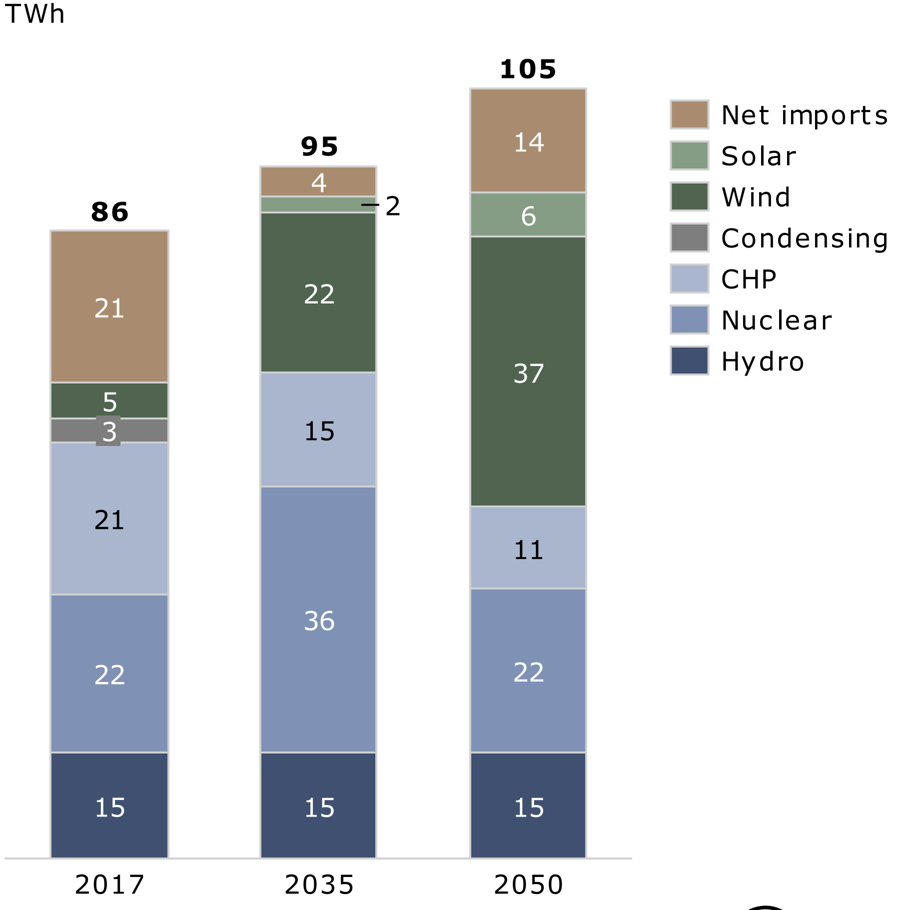
Large scale penetration of wind and solar power

- Wind power is 22 TWh in 2035 and 37 TWh in 2050, solar power 2 and 6 TWh respectively

Electricity production is nearly carbon neutral in 2035

- Use of peat and natural gas and very small shares of oil in cogeneration are the main sources of emissions in 2035 and afterwards only some CHP production with waste and mixed fuels remain as sources of emissions

ELECTRICITY SUPPLY IN BAU SCENARIO 2017-2050



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Increasing generation with renewables, especially wind, and nuclear answer to the increased demand in Low carbon scenario

Increase of domestic generation reduces net imports

- In Low carbon scenario, domestic production increases from 65TWh in 2017 to 110TWh in 2035 and 129TWh in 2050 as a result of wind power investments and high share of nuclear due to new plants and extending or replacing existing ones
- Net imports of electricity from the Nordic countries fall to 1TWh in 2035, after which they will increase to 5TWh by 2050 mostly due to increasing demand and wind-dominated generation mix, where Nordic hydro-powered imports are required to balance the system

Modest decline in cogeneration while nuclear generation increases to 2035

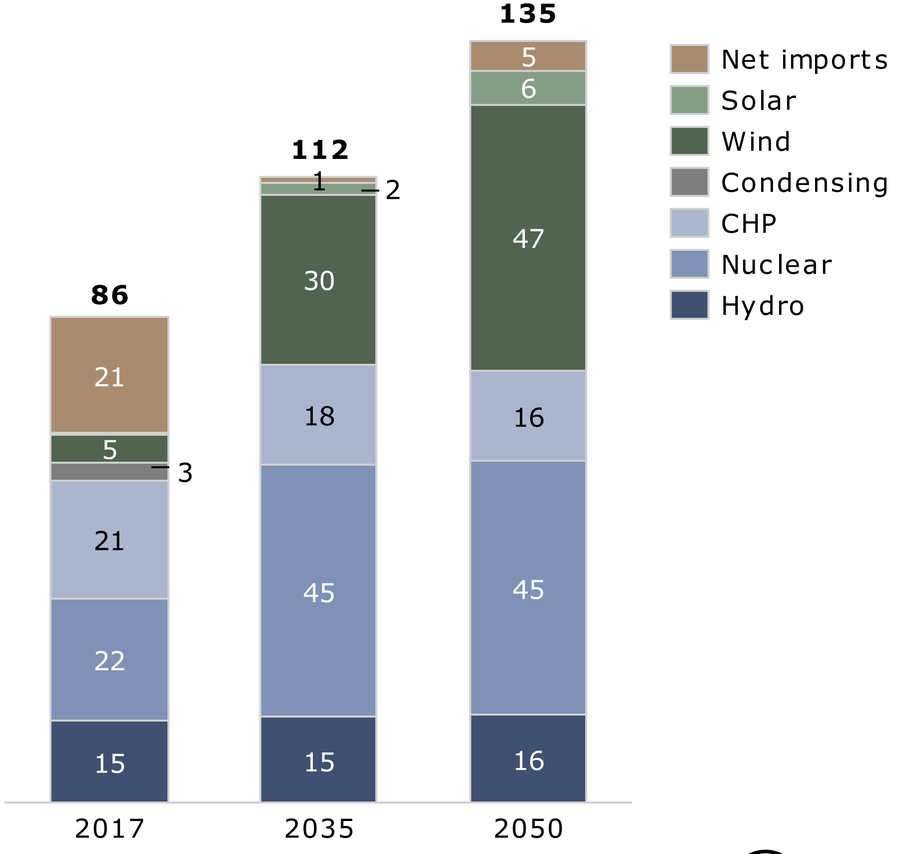
- Cogeneration is expected to fall from its current level of 21TWh electricity to 18TWh in 2035 and 16TWh in 2050
- Compared to BAU-scenario, more of the existing CHP fleet is replaced as higher industrial electricity demand increases electricity prices and thus CHP production remains competitive. The replacements are bio-CHPs and electricity supply is nearly carbon-neutral as in the BAU scenario
- Nuclear generation doubles up to 45TWh by 2035 as two new nuclear plants, Olkiluoto 3 and Hanhikivi 1 come online, and the lifetime of Loviisa plants are extended over 2035. Lifetime of Olkiluoto 1 & 2 are also extended or replaced by a new plant by 2050

Large scale penetration of RES – especially wind power including offshore

- Wind power is 22TWh in 2035 and 37TWh in 2050, of which around 20% in 2035 and 30% in 2050 accounted for offshore wind power with higher load factor
- Solar power generation is the same as in BAU-scenario at 2 and 6TWh in 2035 and 2050, respectively, as it is not seen to answer to the increased demand most of the year due to its seasonality

ELECTRICITY SUPPLY IN LOW CARBON SCENARIO 2017-2050

TWh



Summary of main assumptions in electricity supply scenarios

Technology	Business-as-usual scenario	Low carbon scenario
CHP	Replacement investments of existing capacity are seen to follow electricity price development. In BAU-scenario, electricity prices are assumed to remain at moderate levels thus limiting commercial feasibility of new CHP investments. CHP units in DH networks with one CHP are replaced with HOBs. In networks with more than one CHP, it is assumed that only one of the units is replaced with CHP and others with alternative solutions. Industry CHP generation capacity declines as there are more cost competitive alternatives for power available. CHP units using black liquor are replaced by similar units and some of current fossil fueled CHPs with biomass CHPs. Notable fuel mix changes: - Phase-out of coal by 2030 - Peat usage declines to the technical minimum level set by boiler requirements by 2030. Peat is no longer used in 2040's - Use of natural gas diminishes in the 2030's as existing capacity retires	In Low carbon scenario, electricity prices are assumed to increase due to significantly higher demand. More of the existing CHP fleet is replaced in comparison to BAU-scenario, as they are seen to be competitive against HOBs. Compared to the DH supply in BAU scenario, the share of CHPs remains clearly higher. However, alternative solutions still replace some of the CHP heat production both in DH and industrial use. Industrial CHPs using black liquor are replaced with similar units, whereas replacements for current fossil fuel plants are biomass CHPs and as a result wood based fuel demand for energy use is seen increasing. Otherwise same fuel mix changes concern peat and fossil fuels.
Nuclear	Nuclear generation capacity is based on current permits and plans. Loviisa plant (1000MW) is shut down in the end of 2020's and Olkiluoto 1&2 (1600MW) in 2038. Olkiluoto 3 (1600MW) online in 2021 and Hanhikivi 1 (1200MW) in 2028	Nuclear generation capacity is assumed to remain at a level where new Olkiluoto 3 (1600MW) and Hanhikivi 1 (1200MW) plants are online, and the existing Loviisa and Olkiluoto plants are either staying online by extending permits or replaced by 2035 and 2050
Hydro	No changes assumed to current hydro capacity of 3200MW	Capacity increases resulting in c. +1TWh annual production
Wind	In the current market environment, onshore wind is considered the most cost competitive alternative for electricity generation. Scenario assumes some 300MW of new wind capacity to be built annually between 2017-2050. The scenario is based on current build rate and is in line with SKM estimate[1]	Scenario assumes increased development of wind power at around 450MW of new wind capacity to be built annually between 2017-2050. In addition to onshore wind, offshore wind is exploited especially by 2050 as its potential with higher load factor is seen essential to match the higher demand
Solar	Solar power generation increases 6TWh by 2050 but growth rate is more moderate in the 2020's compared to 2030's and 2040's. Growth rate in 2020's is 100 GWh/a, 200 GWh/a in the 2030's and nearly 300 in the 2040's. Estimate is in line with SKM base scenario	Solar power generation is assumed to remain the same than in business-as-usual scenario due to its seasonality not seen answering to the increased demand
Inter-connectors	Interconnector capacity increases a total of around 1600MW by 2035 and 2800MW by 2050 with new connections mainly between Sweden and Finland and some between Estonia and Norway. Total IC import capacity is around 6800MW in 2035 and 8000MW in 2050.	Interconnector capacity increases a total of around 2100MW by 2035 and 3300MW by 2050. Compared to BAU some of the IC investments are done earlier and there is higher IC capacity between Finland and Estonia. Total IC import capacity is around 7300MW in 2035 and 8500MW in 2050.

1 Sähköntuotannon skenaariolaskelmat vuoteen 2050 (SKM, 2020)

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Geothermal heat and wider availability and utilisation of waste heat sources replace cogenerated district heating

District heat produced by cogeneration declines

- Finnish district heat system is strongly founded on CHP production where currently some 65% of heat is supplied from CHP plants
- The share of cogenerated heat is expected to decline as existing CHP capacities are replaced with HOBs and other alternatives. CHP production declines to 16WTh in 2025 and 9 TWh in 2050

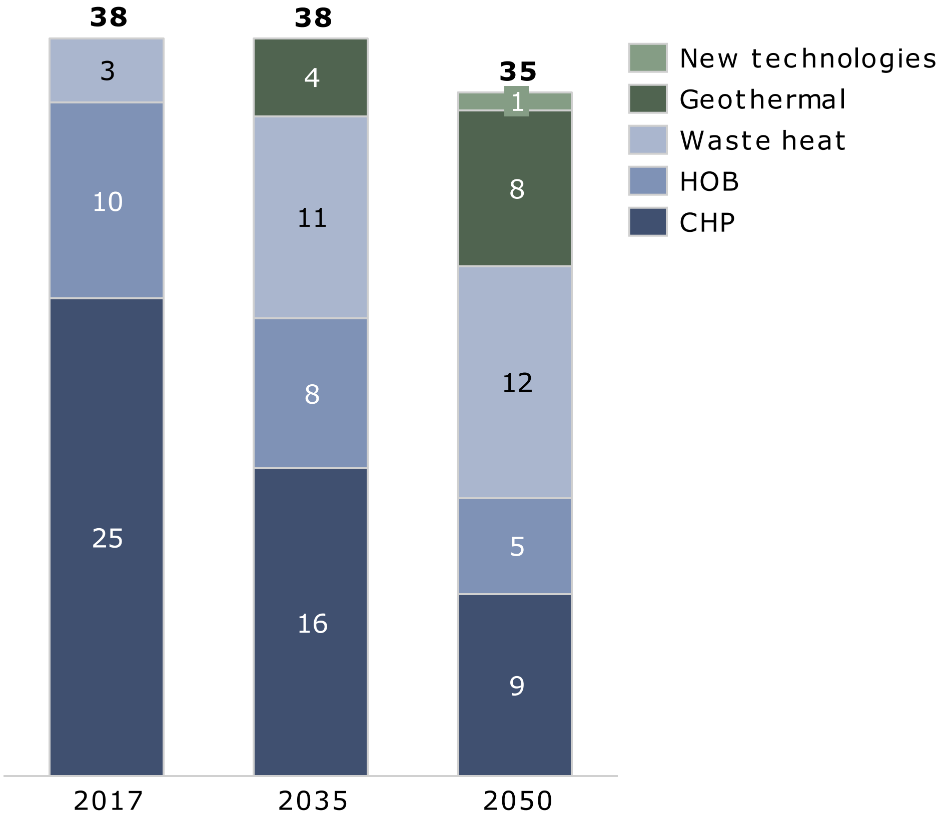
Geothermal and waste heat replace CHP and HOB production

- Waste heat amounts to some 3TWh in 2017 and is estimated to rapidly increase to 11 TWh in 2035 and to 12 TWh in 2050
- Most of this waste heat is expected to be low temperature levels thus utilizable via heat pumps. Growth in data center capacity is the key driver for more availability of waste heat sources. The scenario also assumes 3TWh of heat to be utilised from Kilpilahti
- Geothermal heat is assumed to reach maturity and covers 4TWh of DH production in 2035 and 8TWh in 2050. Half of this heat is collected from deep boreholes and the other half from mid deep boreholes. One deep heat geothermal plant is expected to generate some 200 GWh/a heat, thus 2TWh of deep heat in 2035 would mean 10 plants to be built by 2035
- The amount of waste heat and geothermal in different years is the main uncertainty in the scenario

Possibility of new technologies

- Possible new heat technologies such as SMR (small modular reactors) or CSP (Concentrated Solar Power) are likely to be technically available in the future. 1 TWh is assumed for such technologies in 2050 as a conservative estimate.

DISTRICT HEATING SUPPLY SCENARIO IN BAU SCENARIO FOR 2017-2050
TWh



Fuel use for district heating production declines as heat pumps replace traditional heat production technologies

Wood based fuel consumption remains at current levels

- Biomass usage for district heating is 17TWh in 2017 and is estimated to remain at the current level in the BAU scenario. The increase in biomass consumption as a result of fuel conversions is offset by cogeneration and HOBs being replaced with other heat sources.

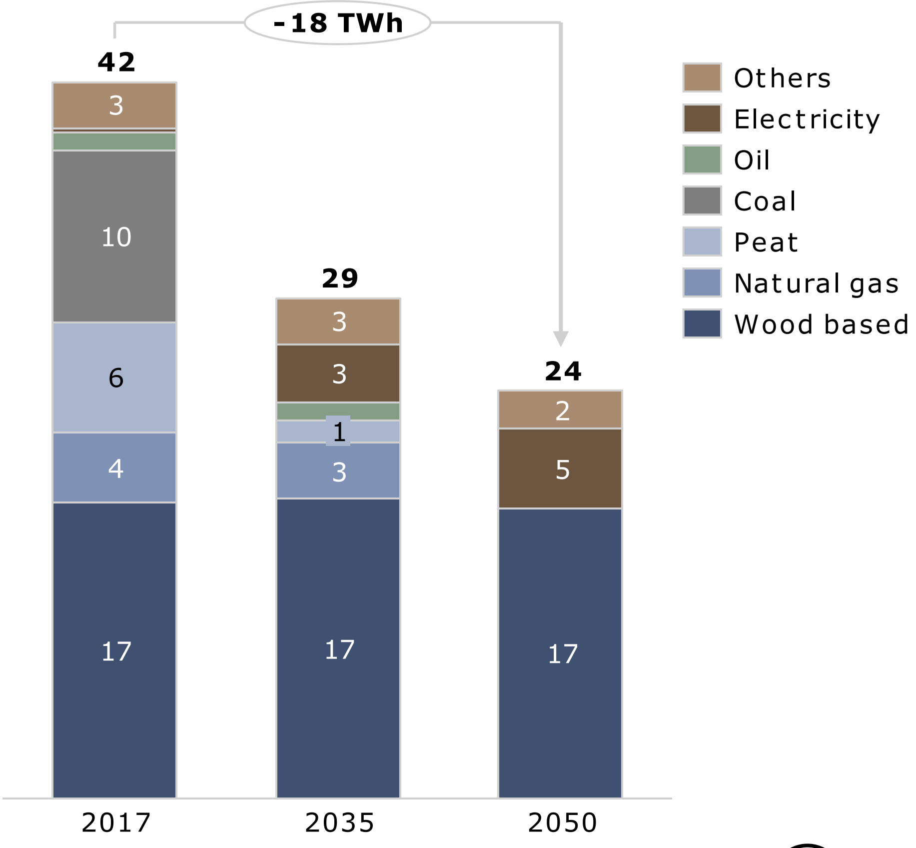
Fuel mix decarbonizes

- Coal (10TWh) is phased out by 2030 as set by the government. The Government is also targeting to reduce peat consumption by half before 2030
- Peat use is assumed to decline to the technical minimum level set by boiler requirements and is expected to be no longer used in 2040's
- Gas consumption declines 1TWh by 2035 due to retiring CHP capacity
- Fossil fuels used in HOBs are primarily used for peak load production are therefore expected to remain constant until 2040. These are replaced with other solutions in the 2040's

Other fuels

- Other fuels category comprises mostly of plastic and hazardous waste, industry gases and residuals waste, fossil part of mixed fuels and reaction and secondary heat of industry

DISTRICT HEATING FUEL CONSUMPTION FOR 2017-2050 IN BAU SCENARIO
TWh



Fuel consumption in power and district heating production has a declining trend

Fuel consumption declines

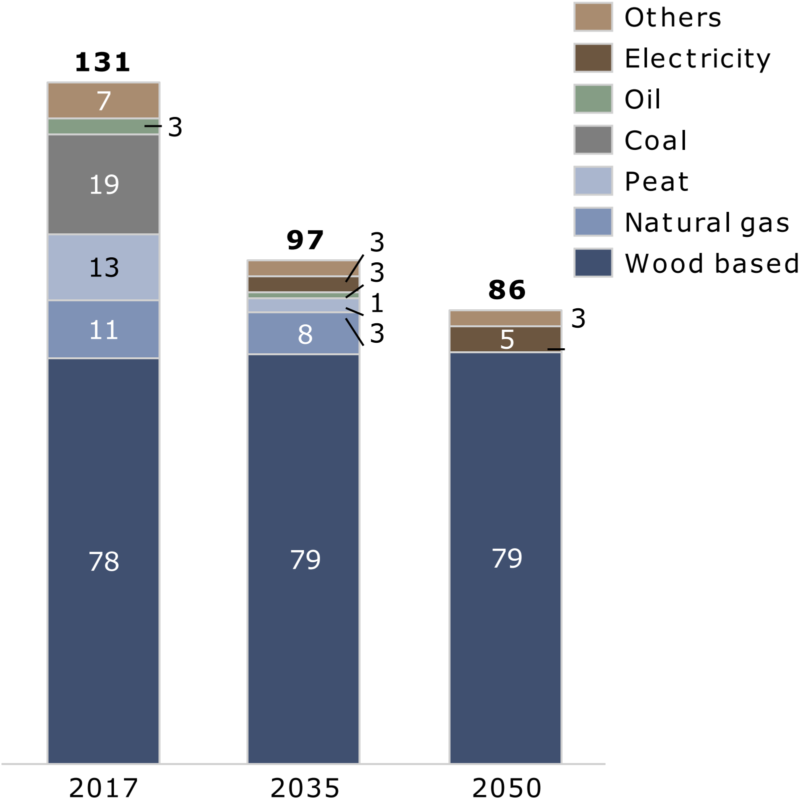
- Fuel consumption used for district heating and power production, including CHP production in industries, is estimated to decline by some 35 TWh by 2035 and 50TWh by 2050
- Fuel consumption does not include separate steam and heat production in other industries
- The main reason for the decline is retiring CHP capacities being replaced with other renewable and non-fuel based heat and power production

Wood based fuels remain the main source of energy

- Biomass and black liquor constitute to almost 80TWh of fuel use in 2017 and this volume is expected to stay at the same level
- Pulp industry is likely to remain strong and all black liquor based electricity and heat production is assumed to remain at current levels
- Some shares of fossil fueled CHPs will also be replaced by bio-based CHPs leading to slight increase in wood based fuel consumption
- Fossil fuel use declines notably as coal use in energy production is phased out before 2035, natural gas consumption declines as existing capacity retires and small amounts of oil is assumed to be used still in the 2040's

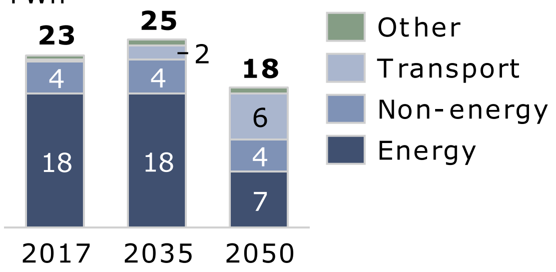
POWER AND DISTRICT HEATING FUEL CONSUMPTION IN BAU SCENARIO

TWh



SCENARIO FOR GAS CONSUMPTION

TWh



- Current gas consumption comprises of 18TWh energy use, 4TWh non-energy use and some 1TWh used in household heating and transport[1]
- AFRY estimates gas use in power generation to decline as current capacity retires. Gas remains as a fuel used in peak load heat production
- Declining gas demand in power generation is partly offset by minor demand growth projected in industry roadmaps
- Biogas use in transport sector could increase up to some 6-10TWh by 2045[2]

1 Statistics Finland (2020) | 2 Action programme for carbon-free transport 2045 (Ministry of Transport and Communications, 2018)

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Higher industrial electricity demand and prices favour CHP production over HOBs and limit alternative methods requiring electricity for heat production

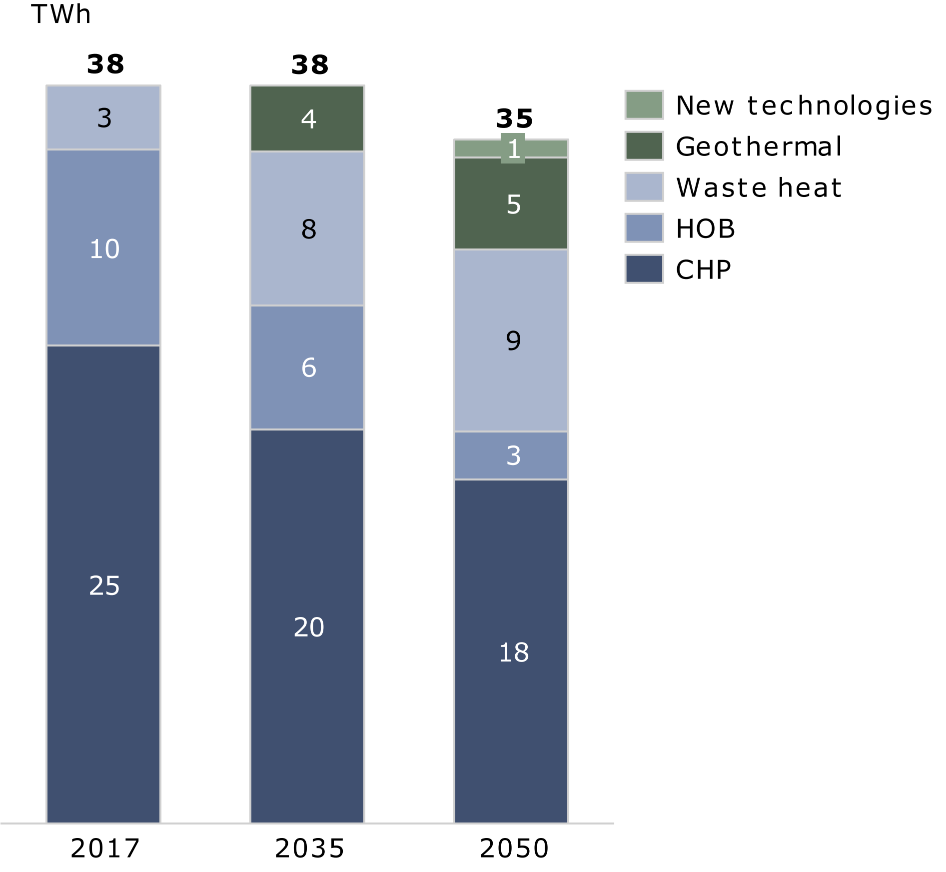
District heat produced with fuels declines

- Compared to the DH supply in BAU scenario, the share of CHP supply remains clearly higher but still decreases from 65% in 2017 to around 50% in 2050. This is due to CHP district heating capacity declines less than in the BAU scenario as most of the existing CHP plants are assumed to be replaced due to high electricity demand increasing prices, making the replace investments feasible
- CHP plants also optimise electricity and heat production and due to high electricity demand the ratio between electricity and heat produced is increased slightly from the current situation as more condensing power is produced
- HOBs see a decrease as they are replaced with alternative energy sources and by 2050 only 3TWh of HOB production remains to supply small distant networks and peak capacity when required. The ratio between CHP and HOB supply is the main uncertainty in the scenario. It depends a lot on the DH networks storage and distribution capabilities to meet the heat demand at all times and e.g. due to cold winters the share of HOB production can be higher

Geothermal and waste heat increase replacing mostly HOBs

- Waste heat amounts increases from the 2017 level of around 3TWh to 8TWh in 2035 as most easily available sources such as data centers are utilised, after which the growth decreases due to higher electricity prices and eventually reaches 9TWh in 2050. Waste heat utilisation is 3TWh less compared to the BAU scenario in 2050. Share of electric boilers has not been estimated separately.
- Geothermal heat is assumed to reach maturity and mainly the deep borehole solutions with higher COP are exploited due to higher electricity prices. This leads to DH production of 4TWh in 2035 and 5TWh in 2050, of which the latter is 3TWh less than in the BAU scenario
- New technologies are assumed to constitute 1TWh of the demand in 2050, which depending on the technological development can be significantly higher

DISTRICT HEATING SUPPLY SCENARIO IN LOW-CARBON SCENARIO FOR 2017-2050



Total fuel consumption in power and district heating production declines but wood based fuels see increase as fossil fuels CHPs are converted or replaced

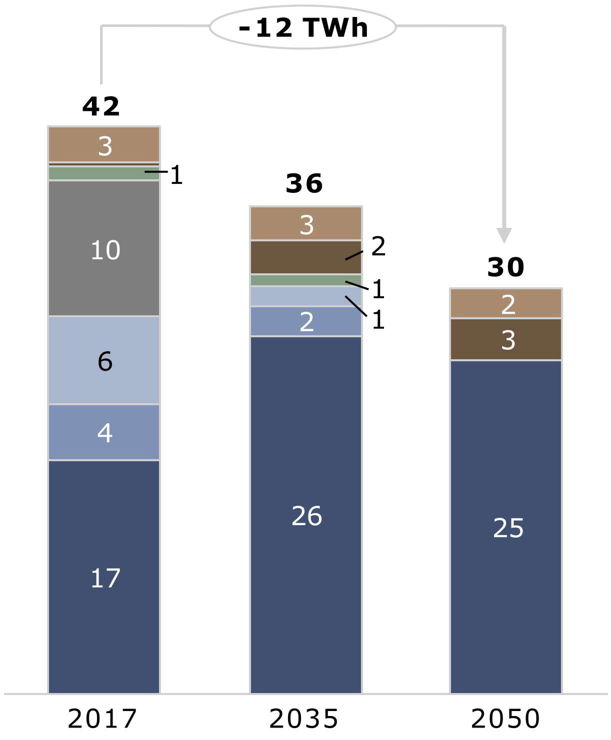
Fuel consumption declines

- Fuel consumption used for district heating and power production, including CHP production in industries, is estimated to decline by some 26TWh by 2035 and 38TWh by 2050, of which respectively 6TWh and 12TWh are due to decrease in district heat fuel use
- Compared to BAU scenario there is more CHP production leading to using fuels but overall trend is still decreasing as some of the CHPs are replaced with non-fuel based heat and power production

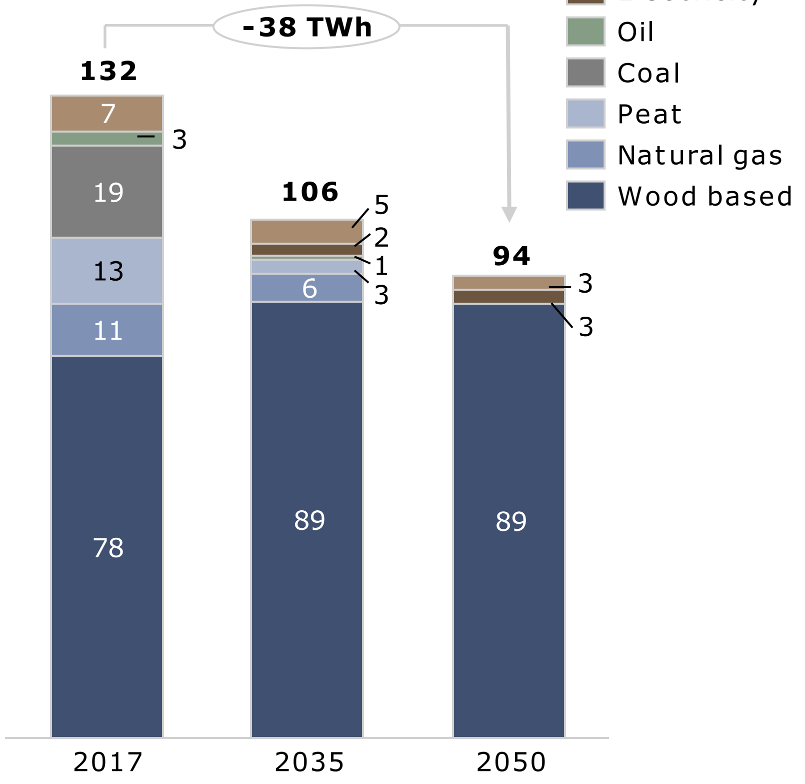
Wood based fuels see increase

- In total wood based fuel use increases by some 11TWh by 2035 reaching nearly 90TWh, after which it stays at the same level
- Most of the increase in wood based fuels is due to fossil fueled CHPs in district heating converted to use increased share of wood based fuels or replaced with bio-CHPs by 2035, whereas black liquor use in pulp industry is expected to remain at current levels
- Fossil fuel use declines the same way as in the BAU scenario as coal use is phased out before 2035 and existing capacities are retired leading to decrease in gas and oil use

DISTRICT HEATING FUEL CONSUMPTION IN LOW CARBON SCENARIO
TWh



POWER AND DISTRICT HEATING FUEL CONSUMPTION IN LOW CARBON SCENARIO
TWh



Power and district heating production reach nearly carbon-neutrality as wood based fuels and cleaner alternatives replace fossil fuels and peat

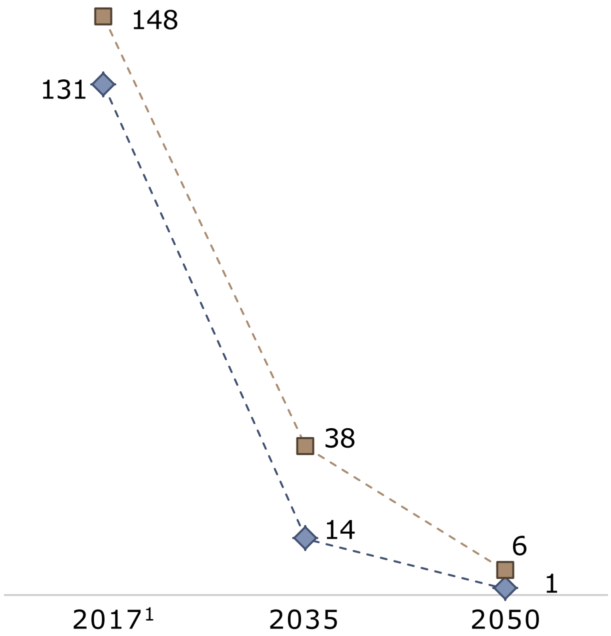
Emissions decrease significantly in both scenarios

- As overall fuel consumption declines and fossil fuels are replaced with cleaner alternatives both in district heating and power production, the emissions see a significant decrease in both scenarios
- Emission factors in the Low Carbon scenario are slightly lower than in the BAU scenario due to more renewable production in comparison to fossil fuel production

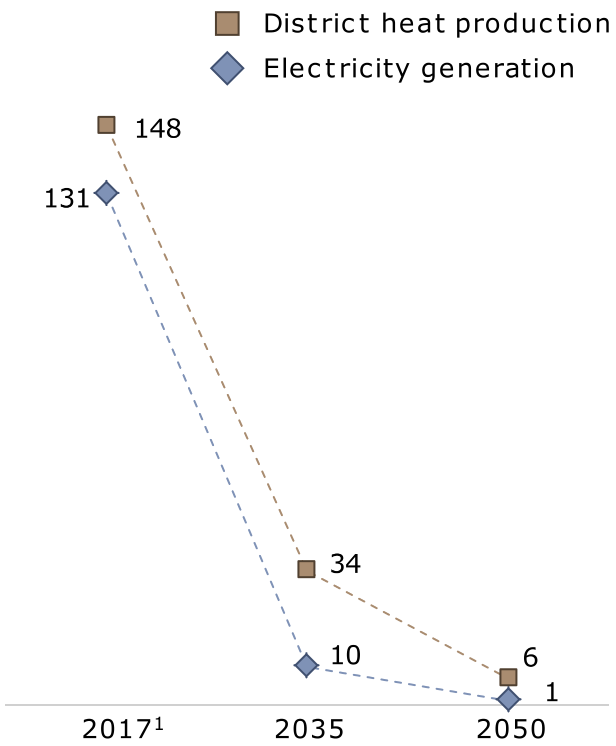
Emissions low already in 2035, only some in 2050

- The decrease by 2035 is mainly due to the phase-out of coal use but also the retirement of existing gas and oil capacities, as well as reduced peat use contribute significantly to the decrease. Remaining emissions are mainly from gas and peat use
- By 2050 there is only some production left with waste and mixed fuels that cause emissions, which overall are in very low level and electricity generation as well as district heat production reach nearly carbon-neutrality

BAU SCENARIO
EMISSION FACTORS OF ELECTRICITY AND DISTRICT HEAT PRODUCTION
kg CO_2/MWh

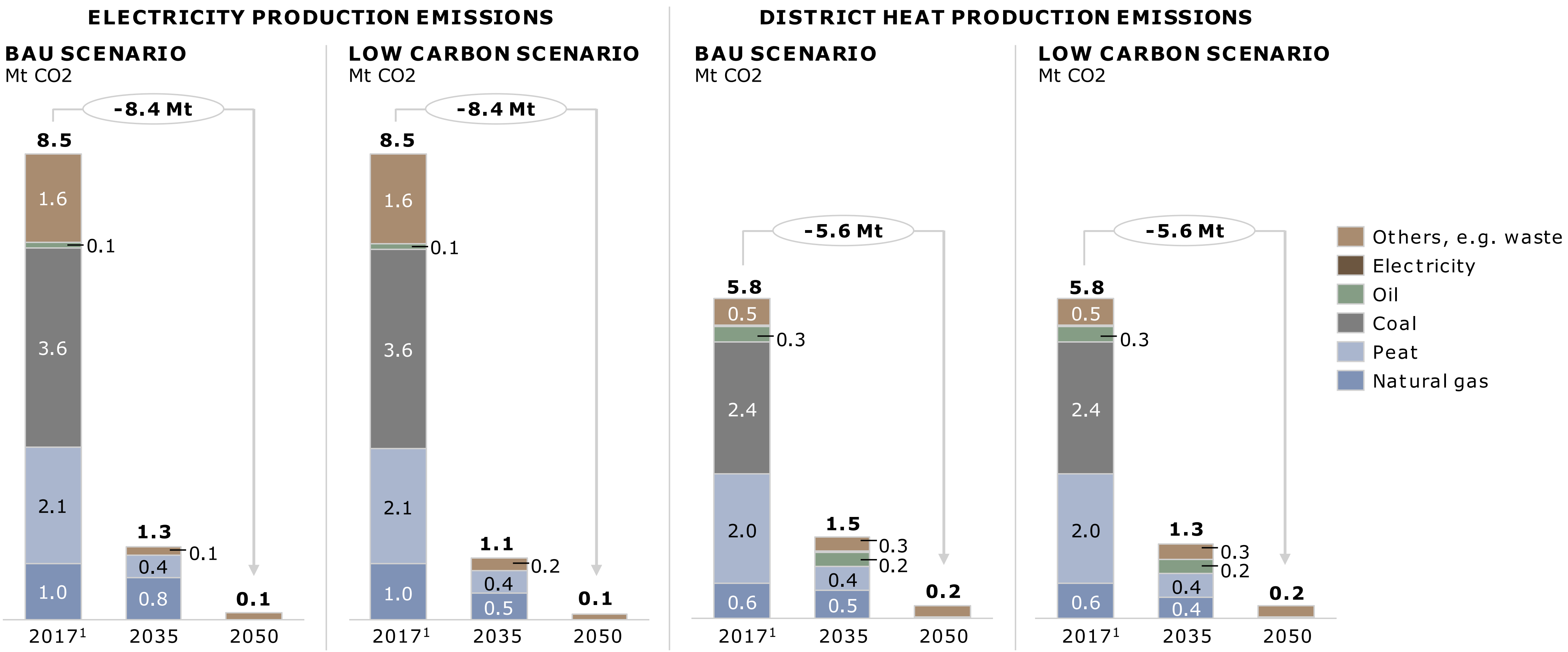


LOW CARBON SCENARIO
EMISSION FACTORS OF ELECTRICITY AND DISTRICT HEAT PRODUCTION
kg CO_2/MWh



1 Statistics Finland (electricity production emissions in 2017), Finnish Energy (emission factor of district heat production in 2017)
Note: Emissions for domestic electricity generation, emissions from cogeneration allocated using the benefit allocation method (hyödynjakomenetelmä)

Power and district heating production reach nearly carbon-neutrality as wood based fuels and cleaner alternatives replace fossil fuels and peat



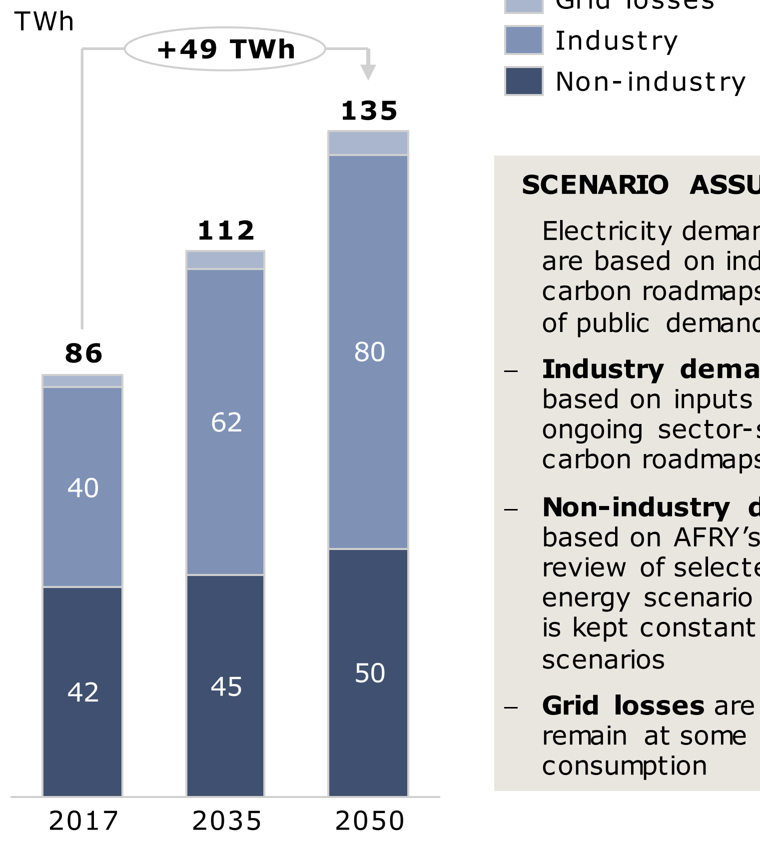
1 Statistics Finland, Heat and power production, energy sources and carbon dioxide emissions 2017
Note: Emissions for domestic electricity generation, emissions from cogeneration allocated using the benefit allocation method (hyödynjakomenetelmä)

Impact on the electricity system in the low carbon scenario

Summary of main assumptions for demand-side modelling in the low carbon scenario

Sector	Assumptions for the Low carbon scenario additional demand compared to 2017 historical demand
Industry	– 50% of the additional demand assumed to follow historical demand profile, which captures changes in demand in seasonal, daily and hourly level – 50% of the additional demand assumed to have a flat demand profile – Some 10% of total industrial demand is assumed to be price-responsive according to current flexibility and assumptions presented in the next slide for additional flexibility, thus this share of the demand is gradually reduced with higher electricity prices
Non-industry and grid losses	– Electric heating of households is assumed to have larger share of heat pumps having a temperature-dependent profile – In transport sector, 50% of the electric vehicles are assumed to follow typical EV demand profile in 2035 and 20% in 2050, whereas rest of the EV demand is assumed to be price-responsive and thus flexible – Services and public sector, electricity consumption of household equipment and transmission and distribution losses are assumed to follow historical demand profile

LOW CARBON SCENARIO



SCENARIO ASSUMPTIONS

Electricity demand scenarios are based on industry Low carbon roadmaps and review of public demand projections

- **Industry demand** is mostly based on inputs from parallel ongoing sector-specific Low carbon roadmaps
- **Non-industry demand** is based on AFRY's high level review of selected recent energy scenario studies and is kept constant in both scenarios
- **Grid losses** are assumed to remain at some 3% of consumption

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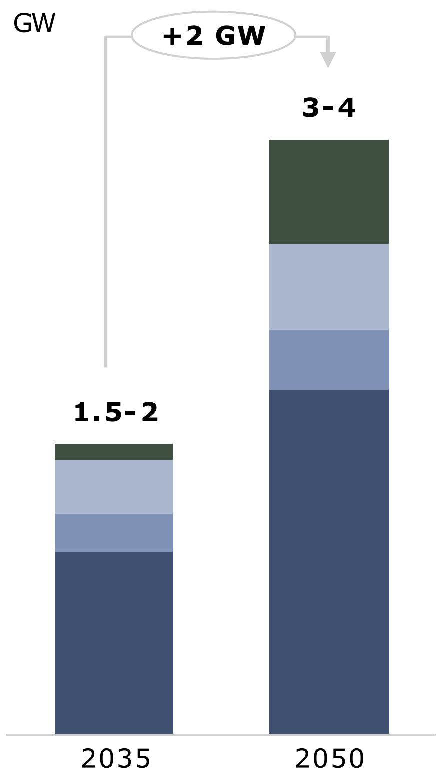
Increased industrial demand in the Low carbon scenario offers an estimated 1.5-2 GW and 3-4 GW demand flexibility by 2035 and 2050, respectively

Industry technology	Description of additional demand-side flexibility in the Low carbon scenario
Power-to-X	– Solutions in chemical and technology sectors offer a significant source of flexibility corresponding to around 60% of the additional demand-side flexibility in industries – Flexibility limited by high investment and storage costs, which are assumed to decrease but still remain relatively high. This causes need for high full-load hours and limit the flexibility to mostly realising during the same day during the highest priced hours
Electrification of process heating	– Estimated to correspond to around 10% of the additional industrial demand-side flexibility both in 2035 and 2050 – More limited flexibility opportunities as electricity consumption is directly connected with continuous processes requiring a stable profile. Demand switching realising mostly within day for a maximum of a few hours that have high price differences
Data centres	– In absolute terms demand flexibility available from data centres increases but relatively its share decreases from around 20% in 2035 to 15% in 2050 – High potential for providing balancing services and mostly used in a short timeframe, as uninterruptible power supply (UPS) system allows disconnecting from the grid and switching to back-up diesel generators quickly
Biomass pre-treatment (drying)[1]	– Share of the additional demand flexibility around 5% in 2035 and nearly 20% in 2050 – Potential source of flexibility for multiple hours within days as biomass can be dried when electricity is inexpensive without significant harm or delay to the overall process

LOW CARBON SCENARIO ADDITIONAL INDUSTRIAL DEMAND FLEXIBILITY



SCENARIO ASSUMPTIONS

Industrial demand-side flexibility estimates are based on annual electricity demand in industry Low carbon roadmaps and identified opportunities based on expert interviews

- **Power-to-X**: 80% of demand flexible with 7000 full-load hours
- **Process electrification**: 25% of demand flexible with 7000 FLHs
- **Data centres**: 100% of demand flexible with 8000 full-load hours
- **Biomass pre-treatment**: 100% of demand flexible with 7000 full-load hours

Sources: Industry stakeholder interviews; Pöyry (2018), Demand and supply of flexibility
1 Note: Not related to drying of biomass used as fuel, but by as raw material in industrial processes.

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Balancing the system with high demand and increased intermittent RES generation is challenging and requires demand-side flexibility

- Electricity demand follows the seasonal trend and reaches new heights during the winter due to the increased electrification of heating and industrial processes
  - In the example week with cold weather Finnish demand reaches an hourly maximum of 20GW in 2035 and 24GW in 2050 whereas the maximum has been around 14-15GW in the 2010s
- Despite the increase in nuclear capacity by 2035, thermal generation can only cover up to around 10GW of the demand in 2035 which decreases slightly by 2050 due to declining CHP capacity compared to 2035. Rest are covered with imports and domestic renewable production, mainly increasing amounts of wind and solar generation supported by hydro generation
- The increasing intermittent renewable generation creates challenges to the system and requires extensive balancing by adjustable hydro generation, exports and imports of electricity between the countries, and use of demand-side flexibility
  - Demand-side flexibility is essential to the system and required to balance generation and demand at all times, as flexible demand can follow the high RES generation hours and demand can be cut during low RES generation hours. All sources of new demand-side flexibility – industrial, heat pumps and electric heating, and electric vehicles – are needed.
  - Wind generation seasonality correlates with demand seasonality and is highest during the winter[1] but in the modelled years can vary during subsequent hours up to around 4GWh/h in 2035 and nearly 10GWh/h in 2050 due to changing wind conditions
  - Balancing measures with Finland's hydro generation are important but somewhat limited as its total capacity is around 3GW and part of it is regulated or run-of-river hydropower, which offer none or only some flexibility of operation for daily fluctuations in demand[2]
  - Imports are mainly available from Sweden and Russia as Estonia is a deficit area and capacity from Norway is limited – Still, most of the available import capacity is required at times to cover high demand periods with low wind generation and imports are in a key role to avoid load loss. Finland also balances the system by exporting excess RES generation, especially during low demand periods but even during periods with quite high demand in the winter when wind conditions are good

1: Tuulivoimatuotannon ja kulutuksen kausivaihtelut (VTT 2018)
2: Vesivoiman merkitys Suomen energiajärjestelmälle (ÅF-Consult Oy 2019)

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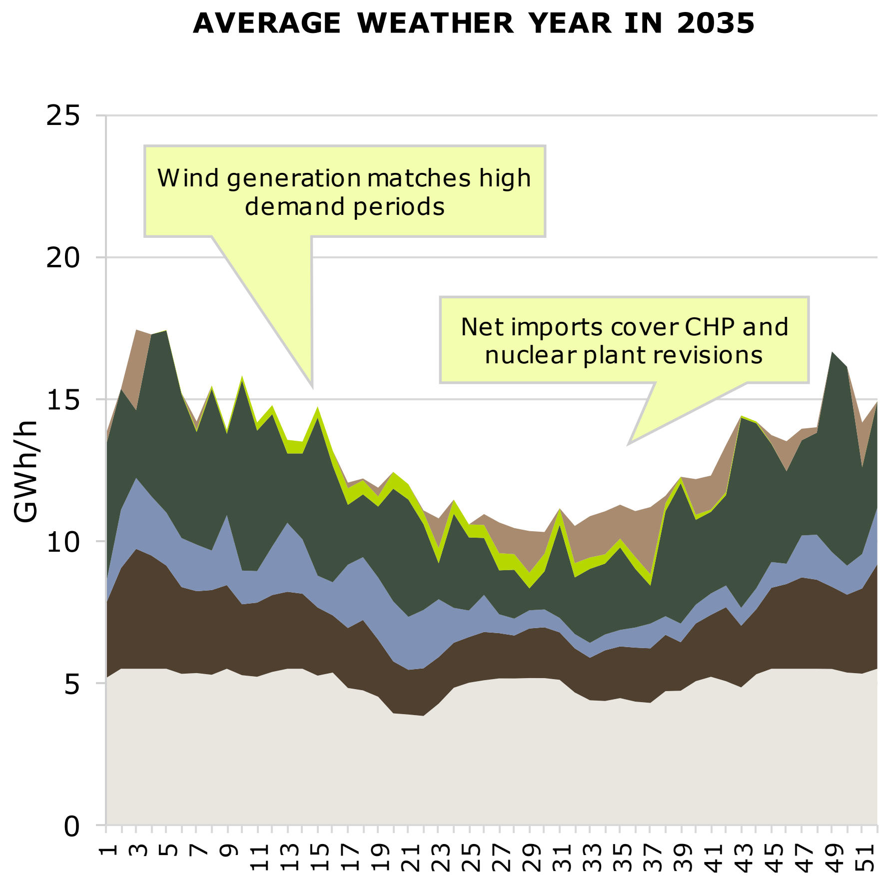
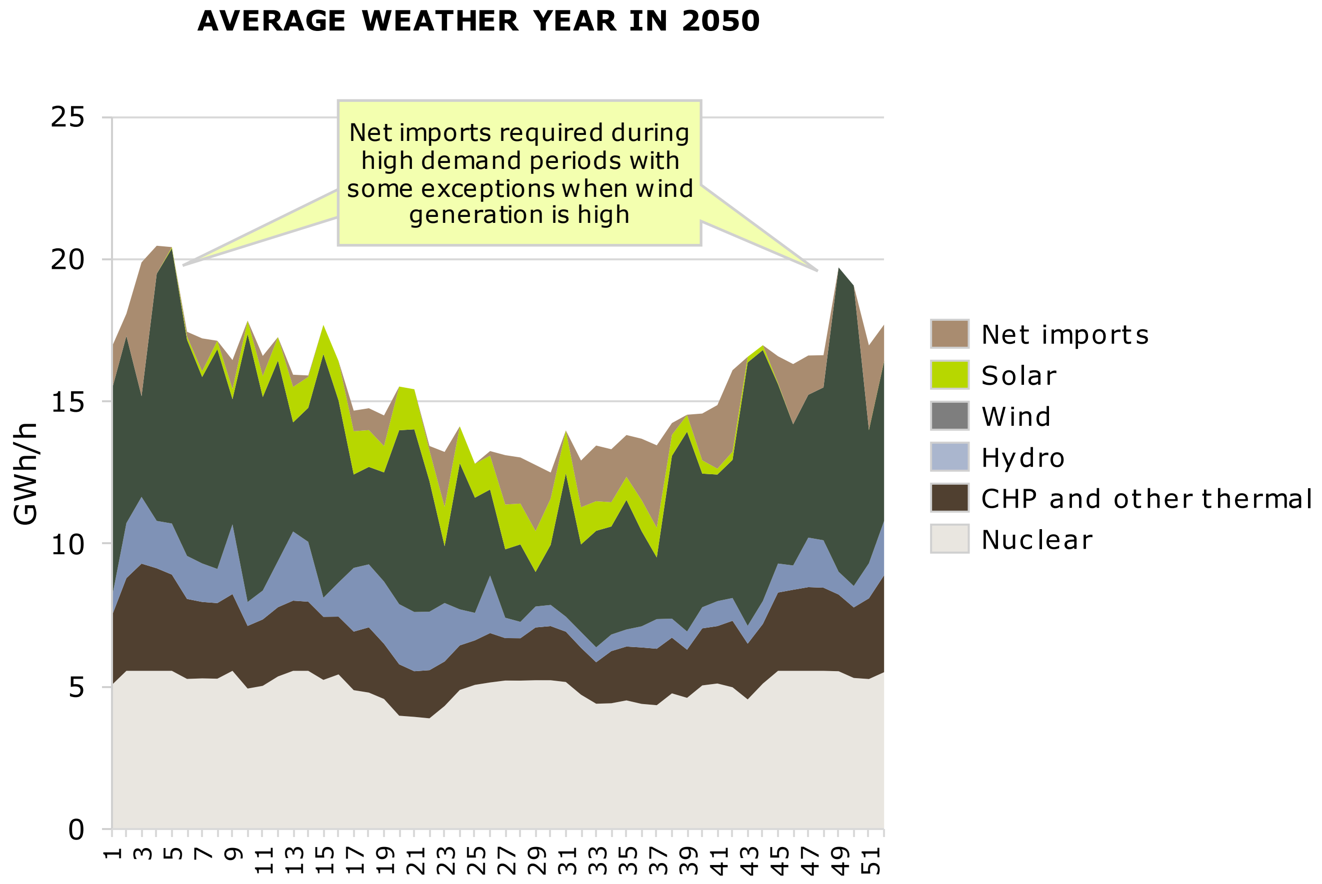
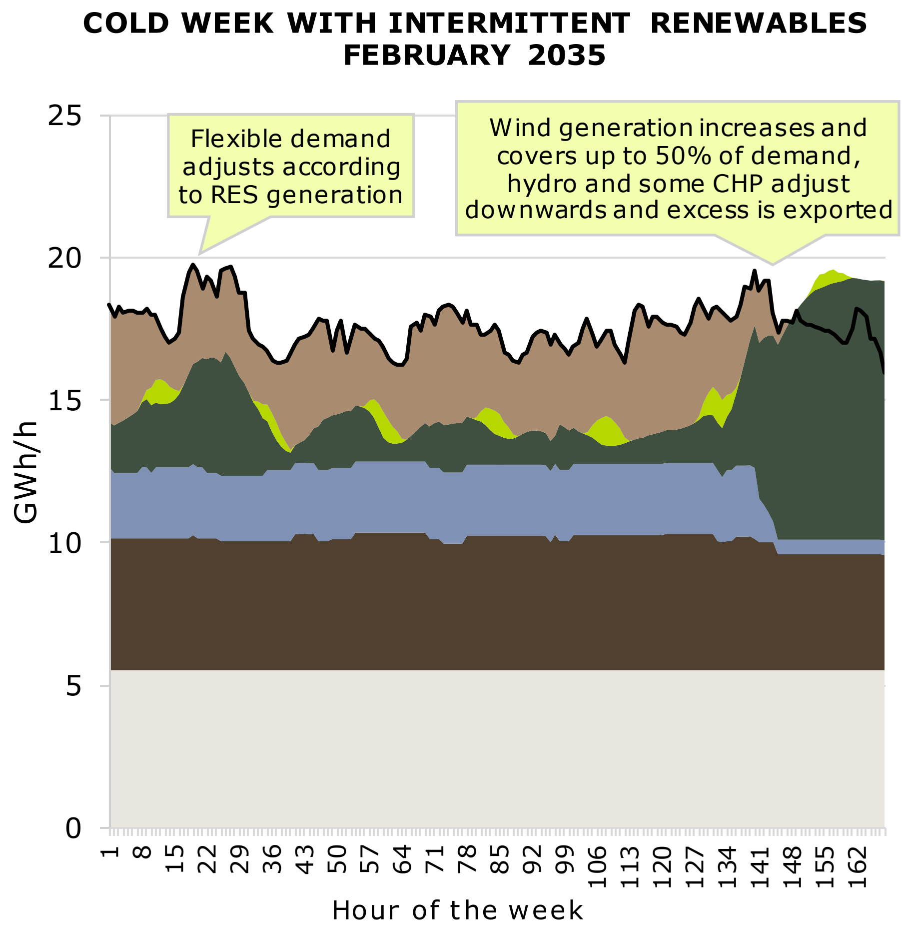
RES seasonality is clearly seen to affect the volume of net imports, which are required to meet demand when RES generation is low

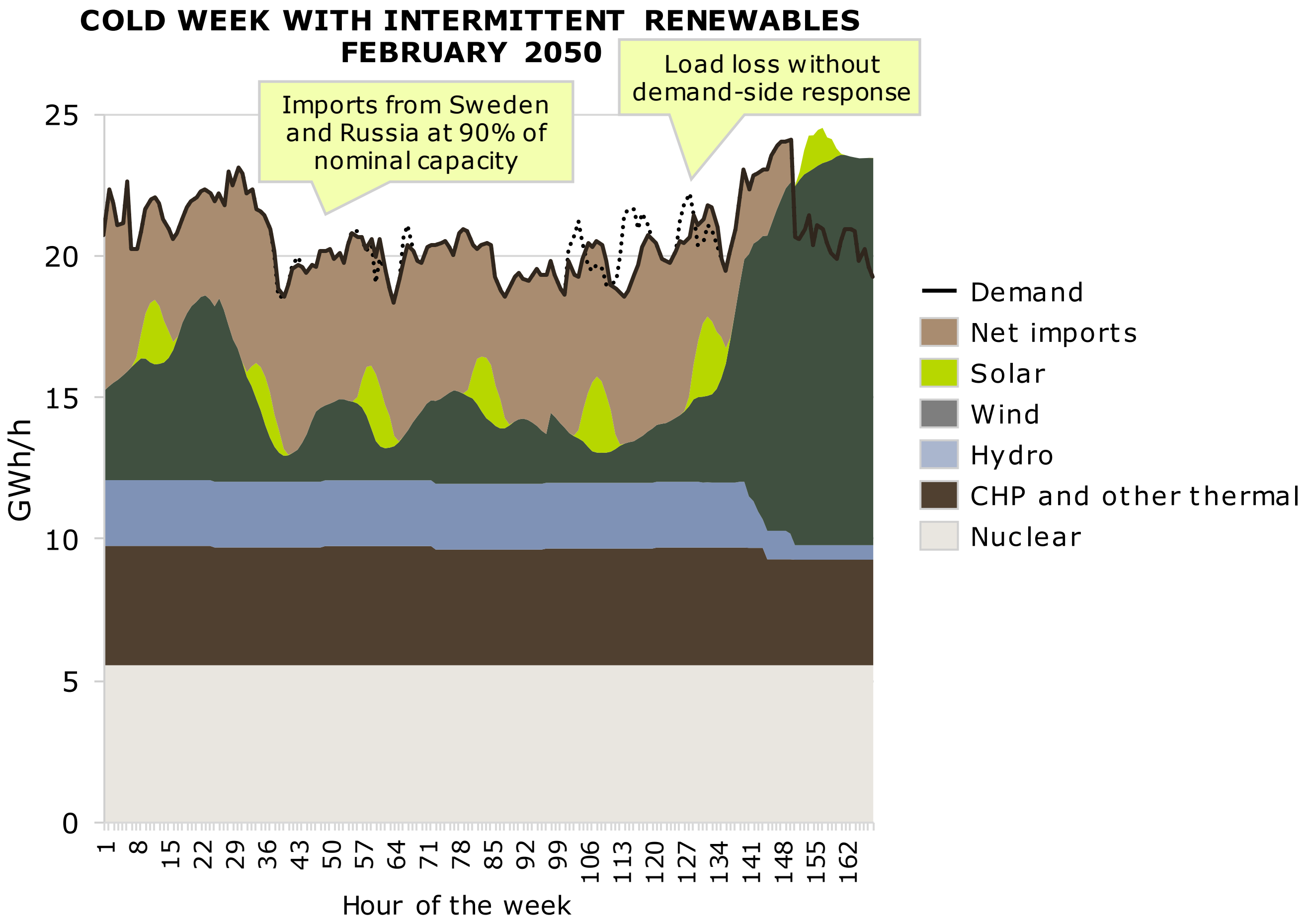




Based on results of AFRY BID3 power market model using weather year 2014

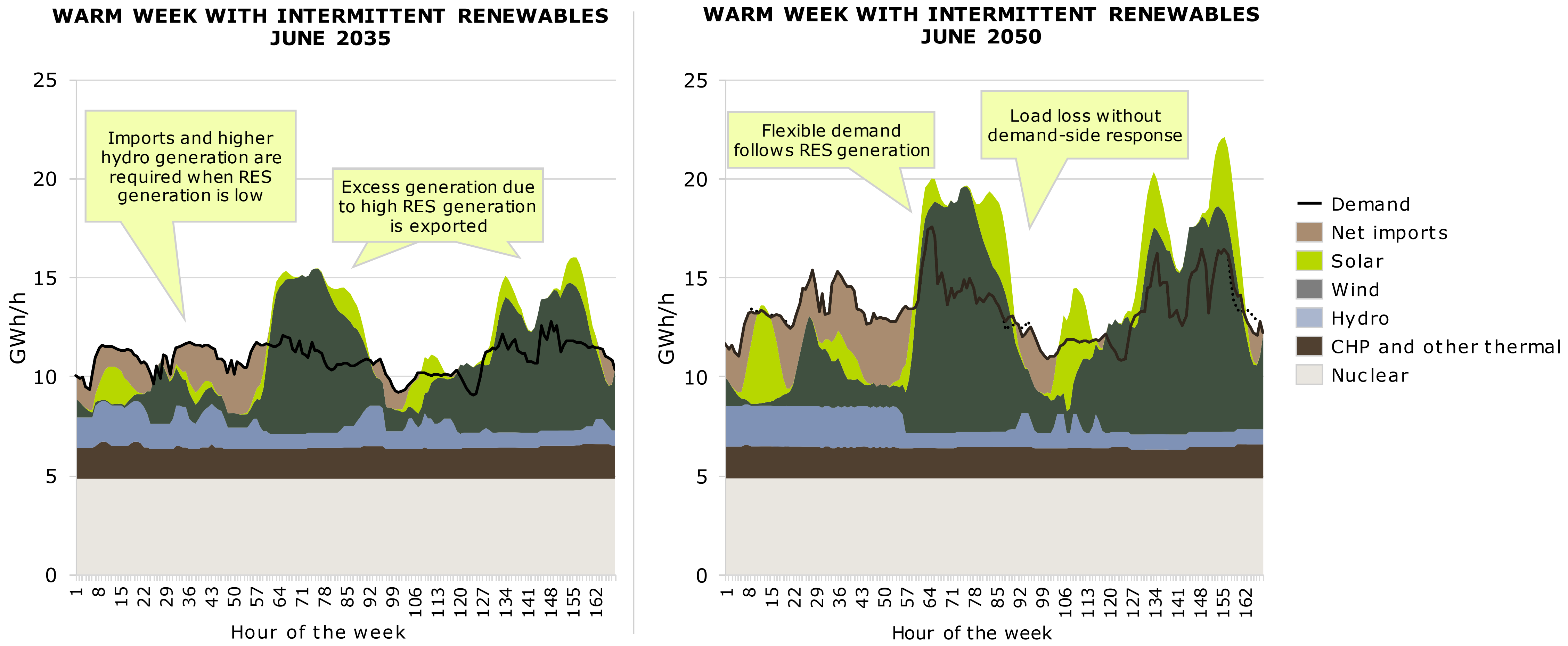
Cold periods with low wind generation challenge the power system, which is then balanced with hydro and imports, as well as demand-side flexibility





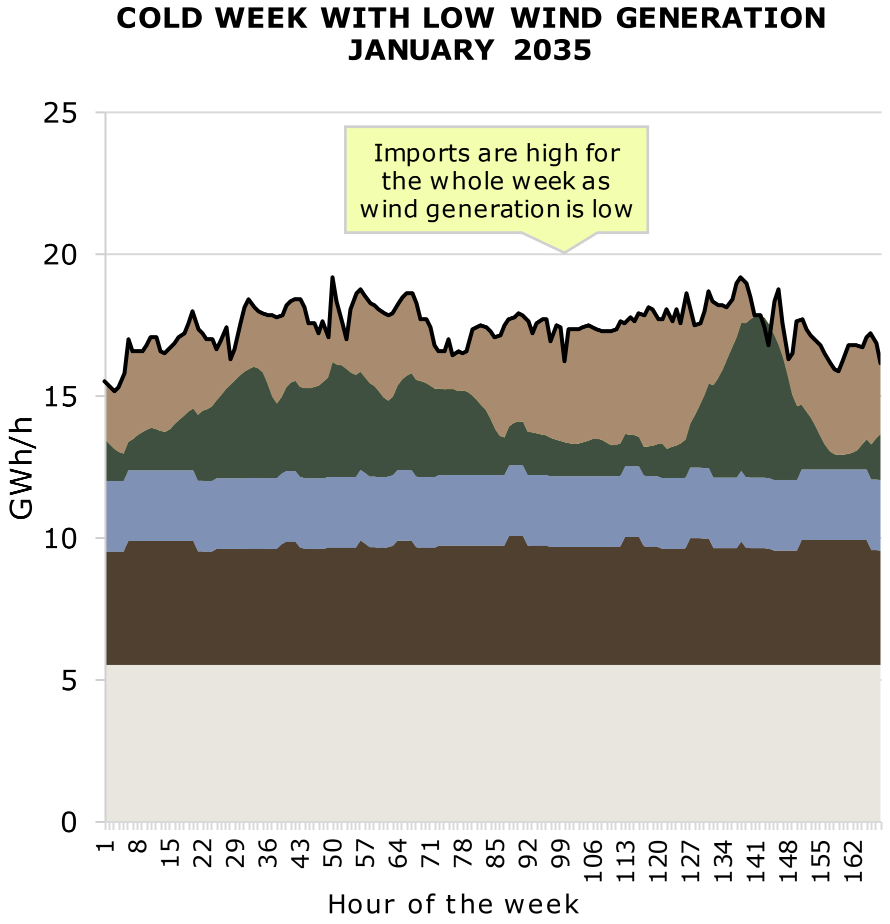
Based on results of AFRY BID3 power market model using weather year 2011, week 8

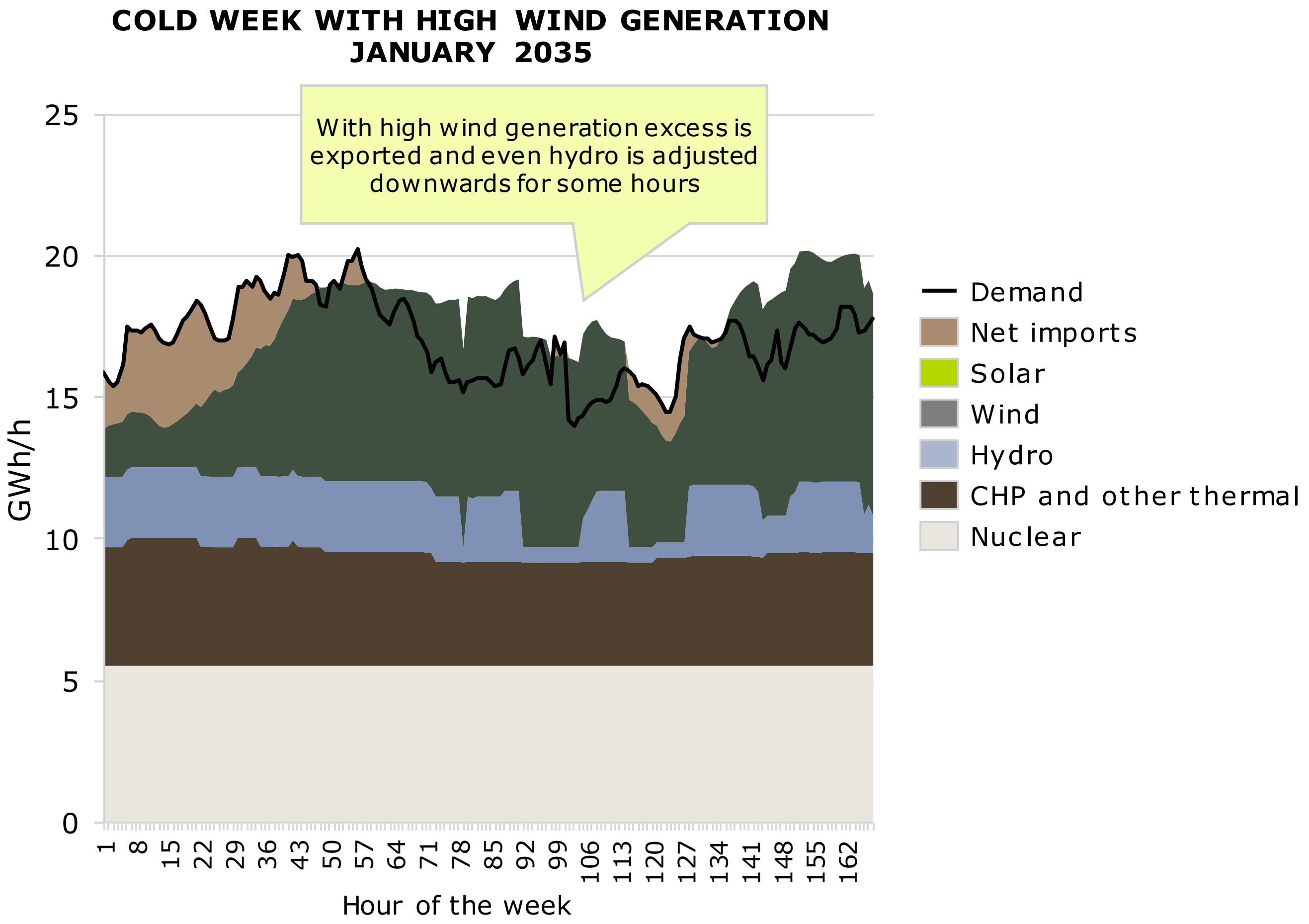
High share of intermittent renewables require adjustable demand and quite high imports/exports even during warmer periods to balance the system



Based on results of AFRY BID3 power market model using weather year 2014, week 24

High share of wind capacity leads to dependency on imports during high demand and low wind generation whereas during cold and windy weeks Finland can become an exporter





Based on results of AFRY BID3 power market model using weather year 2014, weeks 3-4

Conclusions

A substantial increase in electricity generation capacity is needed as a result of the low carbon roadmaps of energy-intensive industries

- Decarbonisation of industries is likely to increase electricity demand in Finland significantly compared to business-as-usual trajectory
  - The scale and timing of the investments especially in electrification of process heating and power-to-hydrogen has a drastic impact on Finnish electricity demand by 2035 and even more by 2050
  - Increased industrial demand in the Low carbon scenario offers significant additional demand-side flexibility
  - All sources of demand-side flexibility should be developed actively to enable a significant increase in intermittent production
- Substantial investments are required in electricity generation due to the massive increase in electricity demand
  - Compared to a business-as-usual scenario, investments in new capacity are needed at a clearly faster pace
  - Costs of clean electricity production have plummeted during the past decade and additional cost decrease is projected
  - For investments to happen in the timescale required and in a cost-efficient way, reliable investment signals are needed together with efficiently functioning electricity markets
- Transmission network needs to be strengthened within Finland and across borders to accommodate increased electricity flows and balancing of the Finnish system in different weather conditions
  - Significant increase in demand and in weather-dependent wind generation require very strong interconnection and efficient cross-border markets so that the flexibility of the wider markets can be utilised to balance the Finnish system
  - Demand concentrates in larger cities due to urbanization and electrification of transport and heat, and at industrial sites
  - Transmission grid investments have long lead times compared to demand/supply side investments hence flexibility measures should be considered as an alternative to cope with potential bottlenecks

District heating and combined heat and power production play a significant role in a low carbon future

- As a result of significant increase in electricity demand in the Low carbon scenario the role of CHP capacity in district heat production is emphasised to ensure security of supply in the power system
  - This has a direct impact on the expected consumption of biomass, which dominates the fuel mix in the business-as-usual and Low carbon scenarios
  - Heat pumps and geothermal heat are expected to play a clearly larger role in the future in district heat production
  - Geothermal heat still has uncertainties with regards to the technical and commercial potential, but is assumed to reach market maturity by 2035 in the scenarios
  - Possible new heat technologies such as SMR (small modular reactors) or CSP (Concentrated Solar Power) are also likely to be technically available in the future
- District heating systems offer sources of flexibility for the energy system in several ways
  - CHP production provides flexibility as heat demand correlates very well with the electricity demand profile in different timescales seasonally and within day
  - Heat pumps and electric boilers can utilise low electricity prices and provide demand-side flexibility
  - This flexibility is enhanced by district heating storages
  - Smart energy control systems and service platforms enable better utilization of, e.g., customers' own energy production and demand-side response, which can support the whole energy system
- Gas use in power generation to decline as current capacity retires. Gas remains as a fuel used in peak load heat production. Declining gas demand in power generation is partly offset by minor demand growth projected in industry roadmaps.

Recommendations for further study

- Given the large changes in the electricity system in the Low carbon scenario, a more detailed analysis exploring *different potential scenarios* is important with regards to for example:
  - Electricity generation capacity especially wind (onshore and offshore, including practical implications), nuclear and CHP
  - Non-industrial demand trajectories, especially electrification of heat and transport and data centres
  - Flexibility supply and demand – development of different technologies such as batteries, different sources of demand-side flexibility
  - Expected locations of new demand and generation and impact on transmission and distribution network investment needs
  - Analysis on a Nordic level considering all decarbonisation targets of different Nordic countries
- The importance of integration of electricity and heat systems are expected to grow in the future, as most of the heat production technologies will either produce electricity (CHP) or consume it (heat pumps) in the Low carbon scenario. This warrants further scenario analysis from the perspective of:
  - Overall heat demand, market shares of different heating solutions and production mix for district heating
  - Assessment of techno-economic potential of new heat production technologies, such as geothermal heat and small modular nuclear reactors
- Adequacy and security of supply of wood based fuels, as the amount of wood based fuels increases significantly in relative terms and in the Low carbon scenario also in absolute terms

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